Efficiency optimisation of the prototyping process for injection moulding

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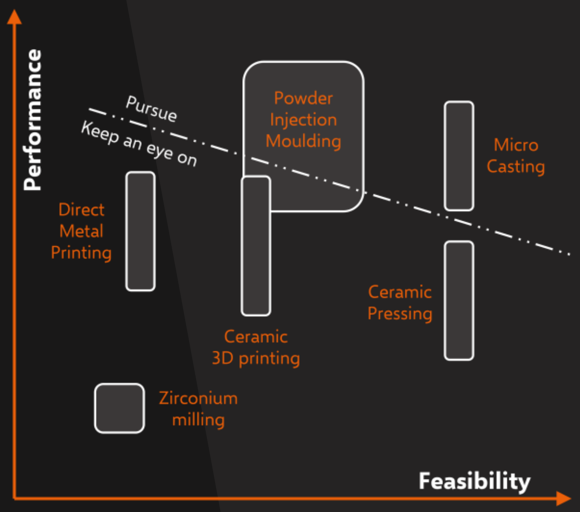
Abstract

This research provides a recommendation for Sonion, a company specialised in the development and production of hearing aids, on the production of moulds for the injection moulding machine.

The goal was to develop a process that reduces the cost and the time to manufacture an injection mould while maintaining a similar accuracy as in conventional mould production. Usually, Sonion outsources the production of injected moulded parts, resulting in parts with a tolerance of ~ ±10 µm that cost €15.000 for a 1000 pieces with a delivery time of 6-8 weeks. For Sonion's development process, which is prototype heavy, this is too expensive and takes too much time. A micro injection moulding machine is acquired to shorten the iteration time of their design process and to reduce cost.

Before and during this research, the possibilities of 3D printing the moulds with a thermal resistant resin were being explored. For that reason, 3D printing with these materials was left out of the scope of this project. Although the accuracy for this method is sufficient, it struggles with the high pressure and temperature it is exposed to while injection moulding.



After identifying many possible manufacturing methods, the most promising techniques capable of withstanding the injection moulding temperature were chosen and validated through testing, research and consulting experts. For a total of six methods, the physical performance (a combination of accuracy, surface roughness and tool life) and the feasibility (iteration time, cost, form freedom and ease of execution) was determined. The performance has been plotted against the feasibility, as can be seen in the figure on the left to form a decision. From the selected six methods, two were recommended for further exploration and investigation; Micro Metal Casting and Powder Injection Moulding. The other methods fell short due to a lack of accuracy, causing iteration time to be too long and the inability to manufacture certain parts of the mould.

The Micro Casting method works on the principle of the lost wax casting and is taken to a higher level by increasing its ability to replicate a shape. Both fully outsourcing the production and in-house production have been tested with similar results; the in-house production being slightly more accurate with a lower surface roughness. Metal moulds can be produced with a tolerance of ±25 µm for a price of around €750 within one to two weeks. It is recommended that for the continuation of this method, first the already acquired moulds are tested and future designs are fully outsourced until higher accuracy and lower surface roughness are required.

Powder Injection Moulding is a method capable of moulding metal parts at a temperature of 190 °C by mixing a fine metal grain with a polymeric binder and therefore could be used to produce a metal injection mould. In theory, the 3D printed moulds should be able to resist this temperature since it is relatively low. After moulding, the part goes into the oven for the polymer to debind and the grains to be sintered together.
A collaboration with the Powder Injection Moulding company Demcon had been setup for testing, but due to misaligning agendas it could not be set in motion. A test with a similar material has been conducted with highly detailed results. It is suggested to explore the possibilities of this method further.

Acknowledgements

I would like to express my gratitude to all people that offered me guidance throughout the course of my thesis and helped me gather all data needed for this project.

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Table of contents

Analysis

To build this research on a solid foundation, all preconditions have been mapped out so a desirable result can be formed.
In this part of the report, the initial assignment will be covered as well as the initial goals. Furthermore, a plan was formed to reach these goals, pointing out how information will be gathered, collaboration with the injection moulding team within Sonion, the planning and the communication with the supervisory team.
Sonion as a company will be reviewed to make a fitting solution. The focus will be on the design process within Sonion and the demand for this injection moulding method. A clear research scope was formed by listing the criteria that were formed based on Sonion's demands.

Introduction

This project takes place at Sonion, a company specialized in the production of speakers and microphones for hearing aids

Because of the small scale of their devices, testing has to be done very accurately. Therefore, the goal is to make prototypes that come as close as possible to the final product. This is done so that testing results of these prototypes approach the performance of the actual product. It is a biocompatible process; the prototyped parts should be wearable and should be able to withstand skin contact. In order to do this as efficiently as possible, it is preferred to make the whole prototype and all its requisites in house.

At present, when prototypes are needed to test on their mechanical and material properties, the production is outsourced to professional injection moulding companies where a soft tooling mould is used to produce ~1000 pieces. This is both time and cost intensive.

Recently, a micro injection moulding machine (The Wittmann Battenfeld 15t) was brought over from their production plant, with the intention to produce a relatively small number of parts that have the mechanical and material properties almost equal to parts from the factory. The production of these moulds currently has to be outsourced, which costs a lot of money but more importantly adds a lot of time between each iteration step.

Figure 1: Wittmann micro injection moulding machine.

The aim of this project is to map out the possible ways of manufacturing a mould in an accurate (20-50 microns of tolerance), affordable (<€20.000 per batch) and quick (<4 weeks of production time) way.

The stakeholders within Sonion are the designers, the people that will produce and use the mould, the suppliers of all used products and Sonion as a company itself. Within this project a balance has to be found between an accurate and quick process while remaining affordable and easy to integrate.

Within Sonion there is a group of 5 employees working part-time, simultaneously with this project, on getting the injection moulding machine up and running. They are not only focussing on the production of the mould, but also on understanding how the moulding machine should be operated. At the start of the project, I will join this team in order to keep up with their developments so the result of this project will be as optimal as possible for Sonion.

The Injection Moulding team (IM team) is, at the start of the project, mainly focussing on the more conventional and available solutions like 3D printing and CNC milling. The problem with these methods is that the 3D prints are not temperature resistant enough and that CNC milling is too complicated and expensive.

At their facility in Hoofddorp, a wide range of tools and machinery is available to prototype with. Besides an assembly machine, injection moulding machine and a CNC machine they have a state of the art resin 3D printer and several high end consumer resin printers. Because of the small layer height and the high accuracy of these machines there is no need for any post processing.

Goal of the project is to design a method that is able to produce moulds for the injection moulding machine. The result will be delivered in the form of a proof of concept, that eventually can be integrated in their prototyping process. The method will consist of 2 parts, namely the practical part of how to produce the moulds, as well as a guide on how it can be integrated as seamlessly as possible.

The mould has a variety of requirements but is mainly based on three pillars; production time, accuracy and cost. A more detailed overview of criteria can be found on page 12 and are the foundation of the project.

Initial approach

Goal
As mentioned in the assignment, the goal of the project is to improve the current situation.
When prototypes are needed to test on their mechanical and material properties, an order is placed of a 1000 pieces at an injection moulding company. There, an aluminium mould is produced, a soft tool, which is capable of lasting up to 100.000 shots. The production of the mould is a costly process because it is labour intense and it takes 4 to 8 weeks; price estimates are often around €15.000. For this price, a very accurate mould is required; the tolerance is below ±10 µm. The main aim of the project is to decrease the time it takes to acquire the mould while maintaining the same accuracy. On top of that, the price per mould has to be decreased (figure 2).

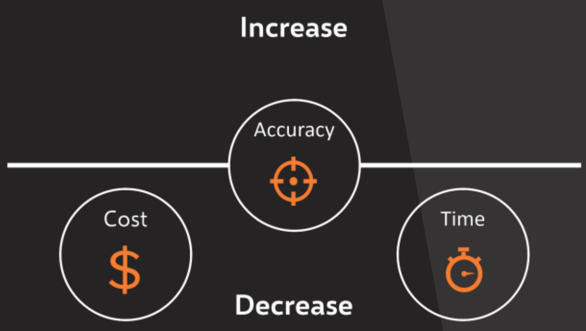


Figure 2: Project goal.

Project plan
The design approach for this project is based on a double diamond (figure 3). In order to make it suit the project better, an adaptation has been made to the second diamond.
During the research phase, diverging is traditionally done, opening the scope to all methods that qualify. First part of this phase is focussed on familiarizing with the process and with the injection moulding machine. When a sufficient amount of data is gathered to form reliable estimations, the scope will be narrowed down by crossing off methods that are predicted not to perform well on a range of set criteria. The methods that remain, will be researched more thoroughly. Once a step to the creation/test and develop phase can be justified due to a high saturation in the research phase, the at that point defined methods can be tested and optimised. It is possible that research in one method and testing another can be done simultaneously.

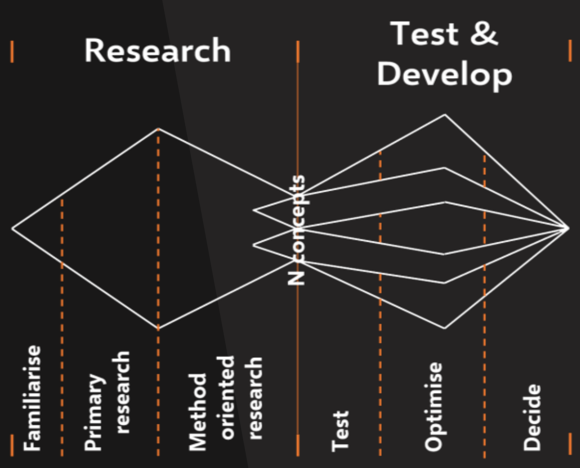


Figure 3: Project plan.

Information acquisition
At the start of the project, collecting data will be done by reviewing papers online but also by gathering information from people within Sonion. Not only fields related to the production of mould, but also other fields will be used to gather information. Conventions on related topics will be looked for and once a certain method is developed, fieldwork will be conducted to gain insights from experts.

Working in the IM team
Joining the IM team will open up an opportunity to gain good insights regarding this project. Experts on 3D printing, CNC milling, spark machining and other prototyping areas can be contacted to investigate what is possible in the labs.
Since this team is also working on the production of the mould, they will be using their extensive knowledge on these topics to manufacture the mould. In order to optimise the result of this project, solutions like CNC milling and the 3D printing techniques that can be done at the facility won't be researched as extensively as other methods. However, the progress of the team on the manufacturing techniques will be monitored closely so it is possible to adapt the direction of the project accordingly.

Planning

Before the project started, a planning in the form of a gantt chart was constructed and intended as a global guide through the project. The chart is a mere estimation of how the 20-week time span can be divided as optimal as possible.

The project started off the 13th of February with a period of familiarizing with the process, the company and the employees. Simultaneously, literature research will be conducted. Different ways of manufacturing the moulds will be found and bridges to other industries might be discovered and applied as well.

During the 6-week research phase, (preparation of) testing the identified methods starts at the 27th of February. Quickly after a promising method is found and analysed, the materials that are needed will be ordered or arrangement will be made for the method to be tested. This is done to make sure that as many different methods as possible can be put to the test. Before ordering, experts are consulted to see what they think of the test and consider it viable and feasible. In week 8 the midterm evaluation is planned, a moment where progress will be reviewed and the direction of the project is adjusted if needed.

On the 17th of April it is expected that most of the possible methods have been tested. At this point, the results will be compared to each other and experts from Sonion and the TU Delft will be consulted. At the end of this 2-week period, a conclusion will be formed that will direct the rest of the project.

Around week 11, the most promising method(s) will be combined, if possible, into one method and then this method will be optimised and prepared to be integrated into the prototyping process at hand at Sonion. During this phase, the method will be used for different types of applications and will be calibrated accordingly. Halfway through this 4-week period, the limitations of the method will be mapped out as a foundation for the integration phase.

From the 15th of May, the method will be integrated for 4 weeks as fittingly as possible in the workflow of Sonion. In this period, in week 16, there will also be the green light meeting. After week 16, the process will be concluded and the final version of the report will be started on the 12th of June. At the start of week 19 shaping the presentation will be started and at the end of that week the report and all appendices have to be handed in.

In figure 4, the whole planning is visualised in a Gantt chart.

Communication

The schedule for team meetings will be constructed as follows. In every first week there will be a meeting with the mentor, the second week will be a meeting with the coach and the third week a meeting with the whole team (coach, mentor, mentor Sonion) will take place.

At the end of each week a progress report will be distributed to the team to make sure all members are aware of the progress and the direction of the project. All are asked for feedback and the reports are covered in the meetings.

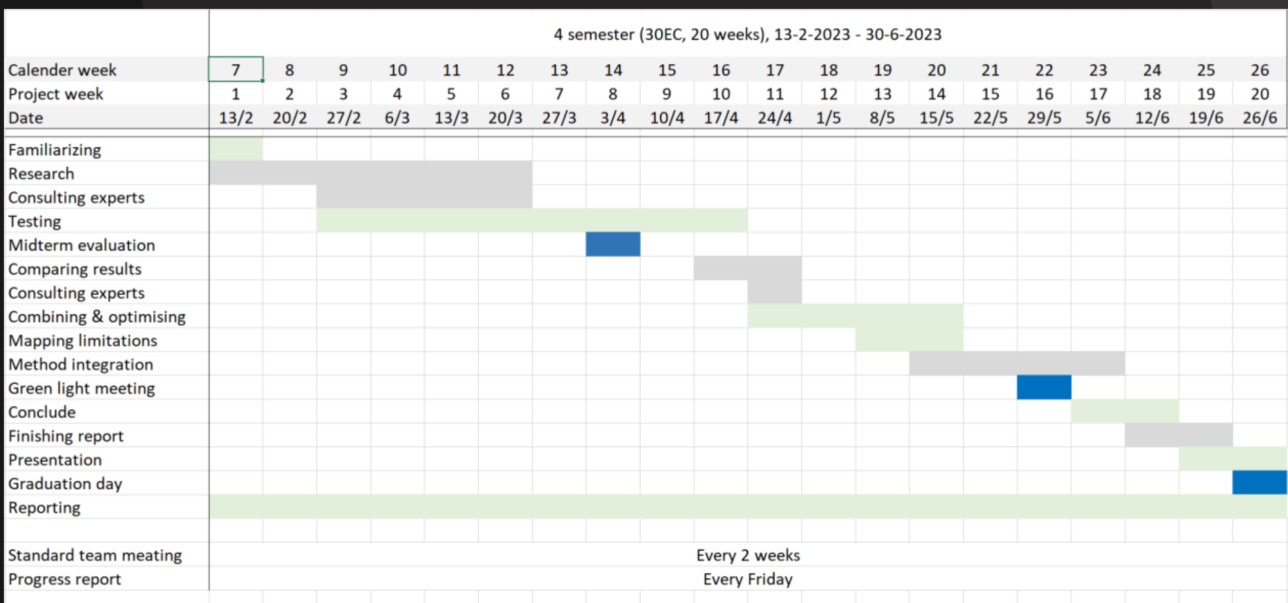


Figure 4: Gantt chart planning

Context

Who is Sonion?

The project takes place at Sonion, a global leader in designing and manufacturing components and solutions for hearing instruments to improve people's quality of life. The company's head quarters is in Denmark, but most product research and development takes place at their branch in Hoofddorp, the Netherlands. Within this facility, new technologies for hearing aids are developed in a prototype intense manner. Most of the production of the hearing aids is done in Asia. Apart from these locations, there are also (sales) departments in Poland, the United States, China and the Philippines.

Figure 5: Sonion Hoofddorp.

Business analysis

The market Sonion operates in, is one of few players. Fifty percent of the hearing aids market share is taken by Sonion, the other fifty percent is for their only competitor, Knowles. Together they compete for "the big five": the five major hearing aids brands. This makes it a tricky business, where disputes about IP rights and patents are not uncommon. Therefore, the need for technological development in processes like manufacturing and prototyping is high.

Development

The main products Sonion offers are speakers, which are called receivers, and microphones for hearing aids. On top of that, they are active in the pro audio segment but also in some consumer headphones. Development and production is mostly done in house as a result of two factors:

- Due to the small scale many part features are difficult to outsource.
- Sonion is very careful that no information is leaked to the competitor.

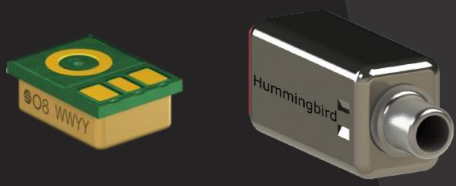


Figure 6: Microphone & receiver.

Design process Sonion

Sonion has a wide range of different speakers and microphones but is also constantly developing new products. Because of the decreasing size of these products, testing of prototypes is getting more difficult. Currently, in the prototyping process, Sonion is using state of the art 3D printers. In case of a prototype that will be tested on its mechanical or material properties, a 3D printer can't produce parts on a level that replicates the properties of a manufactured part. When the need is there to test a part on these properties, the production of the prototypes is outsourced. Around a 1000 parts are being ordered at an injection moulding company for each iteration, where soft tooling is being used

Figure 7: Competitive landscape Sonion

to manufacture a mould for the machine. The cost of such a mould is 15 to 20k and takes ~6 weeks to arrive. This makes it that testing of material and mechanical properties is a difficult process that is prone to time waste. It is possible that a batch of prototypes is ordered and rejected almost upon arrival. In these circumstances, the injection moulding company is contacted again so they can estimate whether the mould can be adapted (for a couple of 100 euros) or whether a new mould has to be manufactured. Therefore, there is a high demand for a method that enables Sonion to acquire prototyping parts that approach the behaviour of the final produced consumer parts in an easy, cheap and quick manner. Within the Sonion facility there is a tool shop with highly skilled workers that are capable of prototyping very fine parts with great precision. Yet, prototyping of housings or cable connectors is very difficult or in some cases impossible with the manufacturing methods provided in the tool shop. Therefore, a micro injection moulding machine, the Wittmann Battenfeld T15, has been brought over from their production plant in the Philippines. This machine should enable the developers at Sonion to make prototypes that have the same material properties as the final consumer products.

Including the user

Within Sonion there is a shift in improving and showing their improvements. Previously, a speaker (within Sonion referred to as receiver) would be improved by increasing the bandwidth. To the customers, the improvement would the presented by showing the graph of the measurements.
Nowadays, the end user is included more in the development process. No longer it's only data that should convince the customer to use Sonion's hearing aids, but also user testing is used to improve and show improvement.

Part samples

Three very different parts, with different levels in difficulty, are used to determine the methods ability to meet the requirements. The parts are a selection from a wide range of very differently shaped parts all with different features. It is likely that for each part, a slightly different way of mould production is required.

Demand

To express the need for this project, but also to be able to adjust a method to the needs of the prototyping process, an estimate has been made on the demand of parts that will need to be prototyped.
This estimate has three major variables; the amount of projects that are running, the type of project and the possible opportunities injection moulding could effectuate once it's more user friendly.

Projects
It is estimated by Sonion that, in the current situation, on average 3 to 5 iteration per part in 1.5 years are outsourced to an injection moulding company. This boils down to 2 to 4 orders a month. Because injection moulded parts can't be ordered in smaller batches, often around a 1000 pieces are ordered at once. The batch volume of prototypes that are required when the production can be done in house is more around 150 pieces.

Predicted demand growth
Once the technology comes available, it is predicted that the demand for injection moulded prototypes increases too. Not only parts that would replicate the behaviour of production parts will be prototyped, but also tests will be conducted on possible new manufacturing techniques (like for example over moulding). It is predicted that the demand for injection moulded parts will increase rapidly.

Conditions

For a structured evaluation of selected methods, a list of conditions has been put together. These criteria have been used in a decision matrices to identify promising methods. The list is in order of importance, but the individual criteria do not have a certain weight. This was done because the criteria should be seen together due to the complexity of the project. A bad score on one of the more important criteria doesn't necessarily rule out a whole method as long as it is useful for some (parts of) the reference parts. Only the temperature resistance and pressure are absolute requirements that have to be met for each method.

Temperature (absolute requirement)

The moulded material, and with that the injection temperature, depends on the part (page 18). For a relatively easy reference part, the intention is to mould PA-66 reinforced with glass fibres varying from 15% to 50% (mass percentage) which requires an injection moulding temperature of around 290 °C. For other parts, the intentions are to use materials like APEC 2097 and PEEK, which would increase the temperature to 315 - 340 °C and 350 - 500 °C, respectively.

All in all, from Sonions perspective, the method should at least support the injection moulding of 15% reinforced PA-66. However, the higher the maximum temperature of the mould, the better. Therefore, a goal is set that the mould should be able to resist a temperature of 400 °C.

Worth mentioning is the fact that the parts produced are of a very small volume, consequently a small volume of melt is injected into the mould. When it leaves the last heated stage of the machine, the nozzle, it has the required temperature. Due to the low mass, the temperature of the melt will decrease quickly. The mould is only exposed to the high temperature for a very short time, which has to be taken into account during the scope exploration.

Pressure (absolute requirement)

Currently, injection moulding is done between 50 and 500 bar for a 3D printed mould. However, the team is still in the testing phase and getting familiar with the machine. Peak values can rise up to a 1000 bar or more, but it is predicted that the injection pressure will be around 100 bar. Because of the unclarity of the reached pressure during the injection moulding process, a high goal is set of 500 bar without any plastic deformation after 10 samples. Because the physical parameters (strength, elasticity region, etc.) are different for materials at different temperatures, the pressure requirement should therefore be considered with an eye on their thermal properties.

Accuracy

The accuracy is a hard requirement set by Sonion. The tolerances are not the same for every part of a certain prototype. Some dimensions have a tighter tolerance than other dimensions because it is constrained by for example a snap fit. As for the temperature, the tolerances heavily depend on the part in question, in general, the parts should ideally have a tolerance between ±20 and ±50 microns.

Iteration time

A distinction has to be made between passive and active time. Active time is the time used by an employee to execute the method, which also adds to the cost of the method. Passive time is waiting time, for example the time it takes for parts to be produced or for orders to be delivered. The time to improve is the 4 to 8 week it usually takes to order a mould from a conventional company. But, for the sake of quick iteration, the production (active+passive time) of the mould can't be more than 7 working days.

Cost

The cost should be split up in "initial investment cost", the initial cost needed to buy i.e. a machine, and the "mould cost", the expenses to produce one mould. Furthermore, the allowed price is influenced by the methods applicability in other processes within Sonion and the performance of the final part.

Tool life

The tool life is the amount of products that can be shot into the mould while staying withing the accuracy requirement and is a result of a variety of criteria. Evidently, the tool life depends on the temperature and pressure resistivity of the mould but also takes cost, ease of integration and time into account. If a mould can be made very quickly and very cheaply with a constant accuracy, the life time doesn't have to be as long as that of a more expensive mould for it to be a profitable method. But, it can only be made very quickly if the process is very accurate and doesn't need any adjusting to achieve this. The whole process has to be taken into account to make a true time estimate.

Form freedom
A wide variety of shapes need to be casted (as can be seen in the part samples), therefore it is beneficial for the method to have a lot of form freedom. Certain design techniques like over moulding and the use of inserts is required.

Ease of integration
Easy integration has the benefit, but it should be seen in relation to how well is performed in other criteria. A method that scores very well in other criteria but is a bit harder to integrate is favoured over a method that partly fulfils the needs but is very easy to integrate.

Surface roughness
The surface roughness is different for every part and could even differ between surfaces within one part. No number can be used to work towards, since it is unclear what roughness will still work for Sonion. The roughness of a method needs to be tested in the injection moulding machine when a mould sample is acquired.

As mentioned earlier this paragraph, these conditions have been used to evaluate all methods in the scope and selected methods in more detail during a later phase of the project. Furthermore, matrices were made for each of the reference part for a part specific method solution.

Injection moulding

Wittmann T15 MicroPower

The injection moulding machine available at Sonion is the MicroPower T15 of the brand Wittmann and is specialised to produce parts on a micro scale. In order to understand the preconditions of this process for this specific machine, the key aspects are covered in this research.

Linear injection moulding

Traditionally, injection moulding is done by feeding material, the feedstock, from a hopper into a heated barrel (Liu et al., 2009). In this barrel, the feedstock is transformed into a melt which is mixed and forced towards the end of the barrel by a helical screw plunger. Through the nozzle of this barrel, the material is injected into the mould. A schematic can be seen in figure 8.

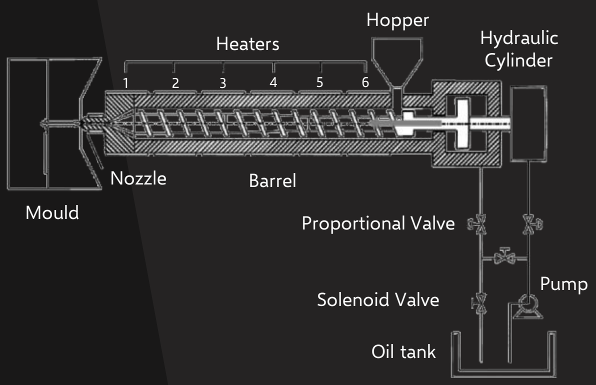


Figure 8: Traditional injection moulding schematic

Controlled outflow

Although the outflow of feedstock can be controlled quite precisely with a linear injection moulding system, a more precise system is required when micro parts are to be produced. As for the traditional method, feedstock is loaded into a hopper that feeds the material into the barrel where it is melted and mixed by a helical screw. When injecting however, the melt is not inserted into the mould directly but is moved into a long cylindrical nozzle. Once the nozzle is filled, the mould is clamped against the nozzle and a long circular rod, the plunger, pushes the melt into the mould (figure 10). The plunger is actuated by a stepper motor and can be controlled very precisely.

Figure 9: Wittmann T15 MicroPower

Effect on the process

Having a more stable injection environment due to the plunger also has a downside; only a limited melt volume can be injected, namely the volume of the nozzle opening. The biggest nozzle size has a diameter of 8 mm and it has a range of movement of 80 mm. Therefore, the maximum shot size of the machine is 4 cm^3, which is something to take into account throughout this research.

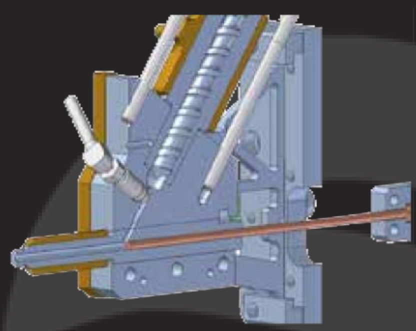


Figure 10: Schematic of the injection unit

Mould configuration

A traditional mould for production would be formed using CNC and EDM technologies from a steel or aluminium block. This makes it that the moulds are very expensive and take a lot of time to manufacture, as mentioned before. In order to avoid this, an adaptable cavity is made where a mould insert can be clamped (figure 11).

This steel block is of a similar size as a traditional mould, the difference being that two sliders can be moved in x and y direction by a bold. When a mould insert is in place, these bolds are tightened by a torque wrench, clamping the insert in place. This master mould is custom made by Sonion. The size of the mould is restricted by the maximum size of the cavity, which is 20mm by 25mm. For this project, this was the only possible way to injection mould, but in the future master moulds with different configurations and cavity sizes could be made. For good moulding results, it is important that the front surface of the mould (the one with the canal, figure 13) is flush with the top surface of steel master mould (upper surface, figure 11). If it sticks out too much, the insert will be crushed by the clamping force when closing the mother mould, but if it falls just inside the mould fleshing will occur while the melt is injected. Active heating or water cooling is also possible with the machine and the master mould, to optimise the quality of the result. This has not been tried yet withing Sonion, but the tools are there to do so.

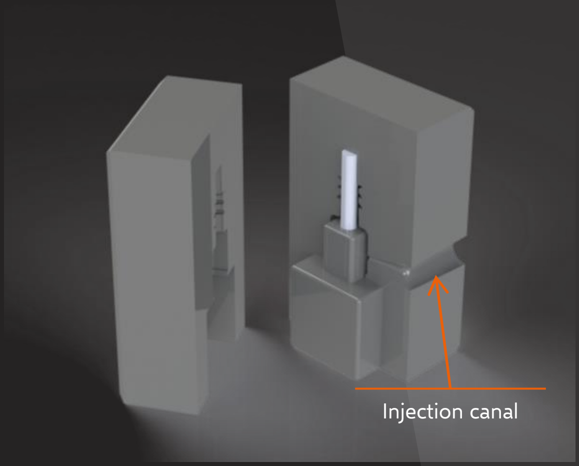


Figure 13: Mould insert example

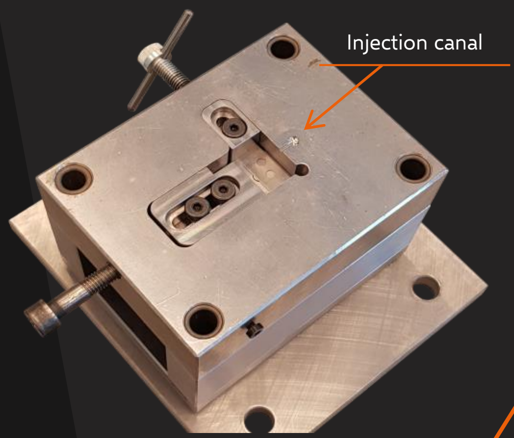


Figure 11: Adaptable insert cavity in master mould

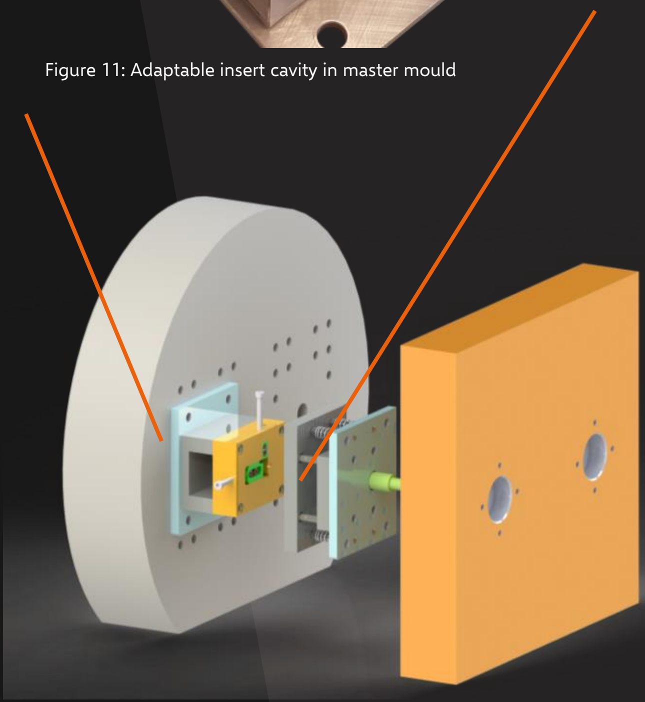


Figure 12: Schematic mould unit

Figure 14: Master mould inside injection machine

Injection moulding

Accuracy

As can be read in the analysis of the reference parts (page 18), the tolerance for most dimensions range from ±0,02 mm to ±0,04 mm. Since replication of a shape can never be perfect, there will always be a geometrical deviation between the intended shape and the produced shape. When a part is injection moulded there will be a loss in tolerance, no matter how the mould was produced. This is important to take into account, because it decreases the allowed tolerance for each method.

Limitations

Testing the deviation between the moulded parts was done by injecting 3D printed [material] moulds with PA66 without glass fibres at a temperature of 280 °C. The part used was a slight simplification of the RIC housing (page 21), which was simplified by the usage of a round metal rod instead of a rod with a chamfer at the end. This part was chosen for the snap fit ribs and the relatively long flow length, which was an aspect the injection moulding team wanted more insights on. The mould can be seen in figure 15. Ideally, the tolerances of the injection

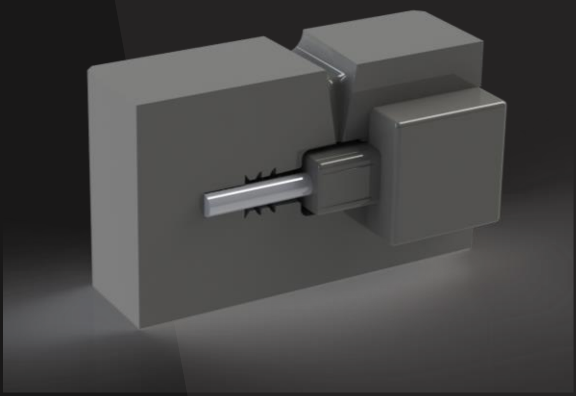


Figure 15: Mould design

moulding step would be tested with the final mould material and procedure and the correct moulding material. Due to time limitations, this was not possible, so an estimation was made with the available 3D prints and mould material.

Method

First the machine has to be set up for the mould and the material, which means setting up the clamping force, the barrel temperature, the injection speed, the change over point and the holding pressure. This is done iteratively by looking at the moulded part which show signs that relate to a certain increase of decrease of a parameter. The machine was setup with one mould, after which a new but identical mould was used to produce a series of parts. One of these parts can be seen in figure 16.

Figure 16: Moulded RIC housing

Failure

Most often the first 3D printed mould wears out before all moulding parameters are optimised. This is after approximately 20 shots for these materials, the wear is shown in figure 17. Due to an error in the mould design, the sprue had to be modified a bit. The wear can be seen mostly in the sprue and around the gate, where plastic is probably

Figure 17: Mould wear

deformed in a semi solid state and cracks have occurred due to the high pressure in combination with the hight temperature.

Part analysis

After completions of the injection of the two prepared moulds, meaning after the moulds had taken too much deformation, some of the parts were geometrically analysed. All produced parts can be seen in figure 18. The first (produced by the first mould) 15 shots can be seen in row 1 and half of row 2. The 12 parts produced after having almost fully setup the machine can be seen onward from the 7th part in row 2 (left to right).

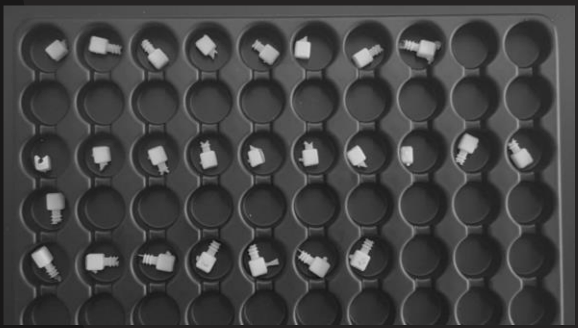


Figure 18: Collection of moulded parts

As can be seen, many of the parts are not fully moulded, only the 4 best parts of the second batch were selected for the analysis. Points on the edge of the RIC housing were chosen for their distinctive position and recognisability, to be measured (figure 19). After establishing the reliability of this method by measuring the same part in two

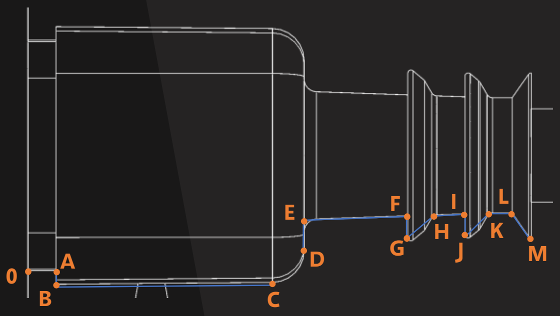


Figure 19: Measured points on the housing

separate occasions, these points on 4 samples were measured with an Mitutoye Smartscope. The coordinates of part 6, 8 and 9 were manipulated with rotation matrices to counteract the misalignment of the part. To calculate the deviation of all points, the average of all 4 samples was calculated for each of the points. The distance from this average point to each of the sample's coordinates is the deviation. The average of all deviations can be seen in table 1. It shows that in general the moulded parts are very similar in geometry, but no conclusion can be drawn just from the average. Important are the deviation peaks, which are within the boundaries (for some coordinates a bit higher than 30 µm). Some of these peaks, at point C & D for example, might be due to the fillet which could result in measuring errors. The full analysis can be seen in appendix I.

Part number	#6	#8	#9	#12
Average deviation from average (µm)	8	8	9	17

Table 1: Collection of moulded parts

Since the shrinkage behaviour is still unclear, it was not accounted for while designing the mould. Therefore, the CAD measurements had to be scaled before comparing it to the measured samples. Biggest deviation were at points G, J and M, because the melt did not fill the entire fillet. Without these corners the average deviation from the CAD model to the samples increased to 13 µm.

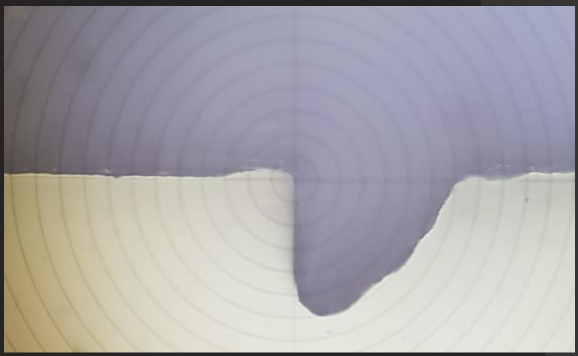


Figure 20: Smartscope aiming at point F of part #12 (part is blue/grey)

The more shots the 3D printed moulds had processed, the rounder the corners got. As can be seen in figure 20, where the inner corner is not sharp anymore but is bend due to thermal deformation.

Conclusion

The average deviation of the first 3 samples was established to be 8 µm with some peaks over the 30 µm resulting in a tolerance of ±30 µm. It is assumed when a material is used with better thermal properties, the average deviation can be kept lower than it is for these parts. Furthermore, this test showed that the 3D printed mould is not able to resist many shots in a row in a reliable manner for a relatively easy to mould material, which brings to light the need of this project.

Reference parts

For the methods to be examined, representative parts had to be chosen for the technologies to be evaluated with. Relevance is the most important criteria for the parts to be representative.

Because the parts used come in different shapes and sizes, it is important for the reference parts to cover different aspects and different levels of size and accuracy.

For each part, different criteria will be covered in this paragraph. In order to get more aware of important features of the part, the way the part is assembled and functions is reviewed. Furthermore, the size and tolerances of these features are mapped. Of high importance is also the material that the part should be made since this influences the temperature resistance, strength (pressure) and indirectly the tool life. Special features, like for example surfaces that have to be glued or snap-fits, are also taken into account.

RIC insert
Motor part
RIC housing front

RIC insert
Part properties

Assembly
This insert is the cap of the receiver unit. Assembly is as follows and can be seen in figure 21:

- The wire goes through the whole of the insert (B)
- Wire is connected to the speaker
- The speaker is glued to the insert (C)
- The housing snaps to the insert (D)

Actual parts are more complex, but can't be shown because it concerns an unreleased product.

Tolerance
To establish what accuracy is required for this part, the technical drawing for production of this part has been reviewed. Smallest tolerances for this product, ±0,02 mm, are for the outer diameters of the dome shaped end and the inner and outer diameter of the cylindrical part that should enclose in the housing. This tube is not equally thick all around, but has a minimal wall thickness of 0.1 mm.

Injection material
The material used for injection moulding is ZYTEL HTN54G3HSLR, which has an optimal melt temperature of 325 °C.

Reasoning
The RIC insert is chosen as a reference part because it is the part the injection moulding team works with at the time of this research. They chose this part because it is currently in demand and it has the right complexity to start with, it is deemed averagely difficult.

Special features
Long term, the surface roughness of the surfaces that have to be glued, need to be close to the surface roughness of that of a production part. For this research, the surface roughness of these surfaces is not taken into account. The roughness can be optimised assuming the chosen method is able to produce the part along the dimensional requirements.

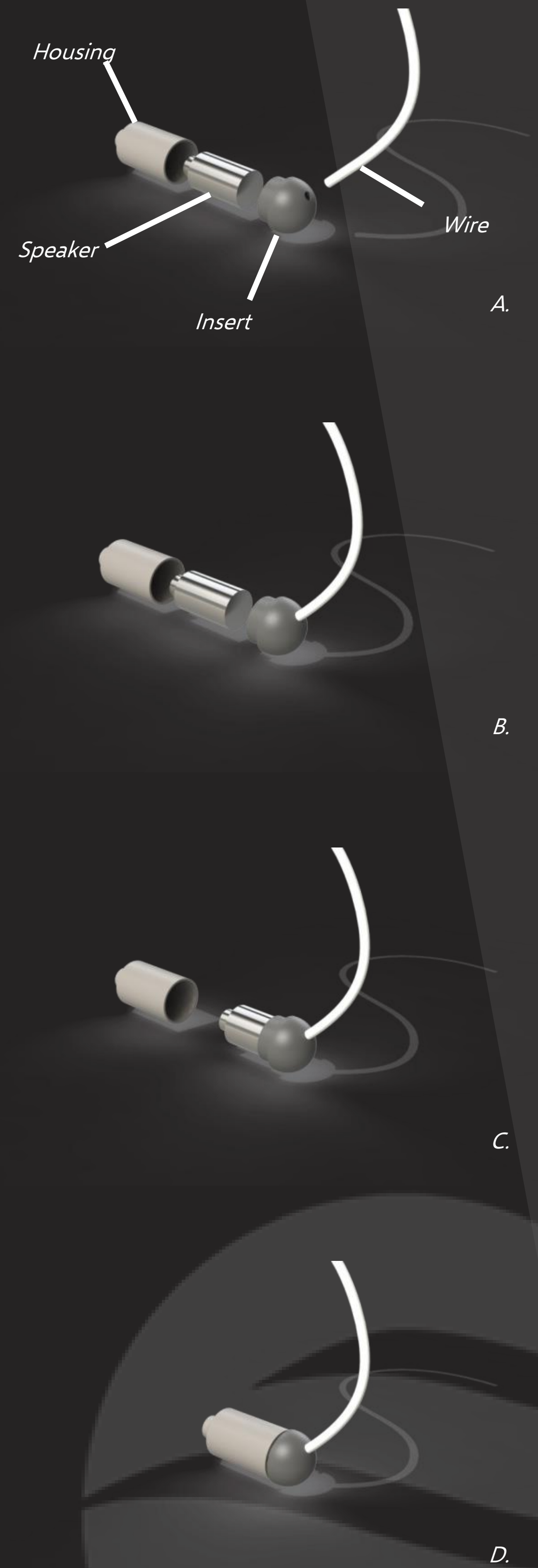


Figure 21: Simplified visualisation assembly RIC insert

Motor part

Part properties

Assembly
This motor part is part of an assembly that can be found inside the receiver. Because the assembly procedure is very delicate, it is important for the part to be strong, sturdy and hard.

Tolerance
For all dimensions of this motor part, the tolerance is ±0,02 mm. The main body is a beam with arms that are 0,38 mm wide (figure 22) which have small features like walls of 0.2 mm wide or fillets of 0.07 mm. This makes it already very tricky for advanced 3D printers that print with a layer height of 10 microns because a fillet, as mentioned before, is in this case only build-up of 7 layers.

Injection material
The material used for injection moulding is APEC 2097, which has an optimal melt temperature of 340 °C.

Reasoning
The motor part was very relevant during the course of this project because there was a high demand for the part to be moulded. 3D printing and injection moulding by hand resulted in too little accuracy and parts that were too flexible and soft to use. For the assembly process it is important that this part is as rigid and hard as possible. Therefore, this part has to be made out of a very hard and strong material like APEC 2097.

Special features
The size and low tolerances make this part suitable as a reference to determine the maximum capabilities needed of a method. Another difficulty of this part is that it can't easily be turned into a two-piece mould. Extra alignment measures need to be taken to ensure the solidity of protruding pieces on one mould half. Designs can not be shown due to the sensitive and secret nature of these parts. The RIC insert covered previously can be seen as the minimal performance of a method, this motor part is more of an ultimate goal. To illustrate, the size of this part is shown in figure 23, that shows a render with the motor part placed on top of the coin.

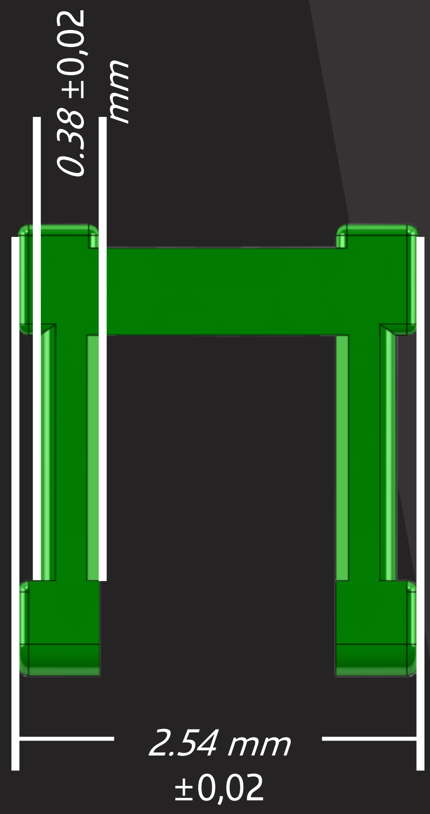


Figure 22: Key dimensions motor part

Figure 23: Motor part on coin

RIC housing front

Part properties

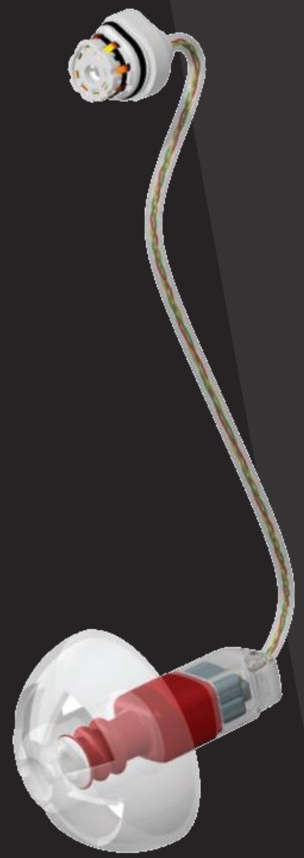


Figure 25: RIC assembly

Assembly

The RIC front housing is the casing around the receiver and has the dome and the rear housing attached to it. The part is glued to the rear housing and the dome is connected with a snap fit. A semi exploded view of the assembly of the red front housin can be seen in figure 24.

Tolerance

As for many of the tolerances of the previously introduced parts, the radial tolerances range from ±0,02 mm to ±0,04 mm. Only the longtitudal dimensions differ, with the dimension from front to back having a tolerance of ±0,1 mm. Important are the dimensions of the snap fit ribs, which have a tolerance of ±0,04 mm on the diameter and ±0,02 mm on the 0.05 mm radius fillet.

Injection material

The RIC front housing is made of PA66 filled with 30% glass fibre (Ulrtamid A3EG6), which has a recommended injection moulding melt temperature of 290 °C. Temperature wise, this is the easiest part to injection mould out of the three reference parts.

Reasoning

The RIC front housing was chosen for this research in collaboration with the IM team. For moulding developments, a mould was needed with a long flow length while still being thin walled. The thin-walled feature was important for the 3D printed moulds to hold up longer, since shots with more volume are heavier on the mould. Furthermore, the snap fit is an interesting feature to test. The role of the availability and the relative ease of moulding of this material also played a role in the decision.

Special features

Because the part has to be fitted to a lot of different key parts in the assembly, many dimension are restricted by low tolerances. Compared to the RIC insert, where the dimensions for the wire hole are not as important of that of the snap fit, this part has to live up to all of the dimensional requirements.

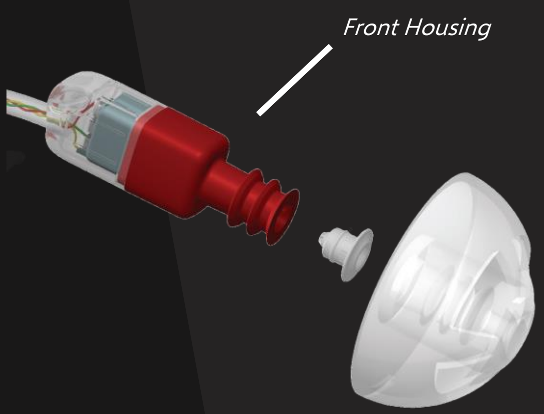


Figure 24: RIC front housing, explodes view

Scope exploration

After establishing the scope, so the needs and conditions, the exploration phase was initiated. This started off with an online research to map out all possibilities. All progress was tracked in a decision matrix with all criteria on one axis and possible methods on the other axis.

After saturating the scope, the methods were researched more thoroughly to give better estimations on their performance. During this process, the focus was on finding method properties that would eliminate the method.

First part of this chapter will be about the rejected methods, after which a more detailed description will be givin on the conventional soft tooling method and the methods chosen to continue exploring.

Research

During the research phase, a wide variety of manufacturing methods have been investigated. The emphasis was mainly on finding a feasible, easy to integrate and well priced method. In order not to miss possible opportunities, also state of the art technologies have been reviewed. Although these methods are as of yet only possible in very advanced laboratories, they could be identified as possible recommendations for the future because of their promising accuracy, strength or temperature resistance.

Approach
The methods were categorised to give structure to the research process.
Research categories:

- Subtractive
- Additive
- Deforming
- Hybrids

Furthermore, some micro joining techniques have been researched to keep the possibility of combining techniques open.

Culled methods
A wide range of methods have been researched and evaluated, which is summarised in an evaluation matrix (appendix II). This was done to visualize in a clear manner what methods were promising and which were not. In this paragraph, the methods that didn't make the cut will be highlighted. To do this in a structured manner, shortcomings have been categorised. Important to mention is that culled methods will be kept in mind to be added when criteria or circumstance change in a later stadium.

-2D manufacturing-
Methods that are very precise and can be done with materials that withstand the high temperatures and pressure, but can solely be applied in 2D. These methods could be used for the manufacturing of the mould if the design would be split up in many layers. A beam of light or electrons is used to cut out a certain shape. These layers would be formed in the right shape and then joined, creating a layered mould. For this method also joining techniques have been reviewed, like ultrasonic welding, laser welding and special types of metal glue, to join the individual layers. The joining step of this method would result in additional time, it would be difficult to integrate and it would increase cost. Furthermore, errors in these steps make the method prone to accuracy loss.
The methods referred to:

- Laser Beam Machining (figure 26)
- Electron Beam Machining
- Photo-Chemical Machining

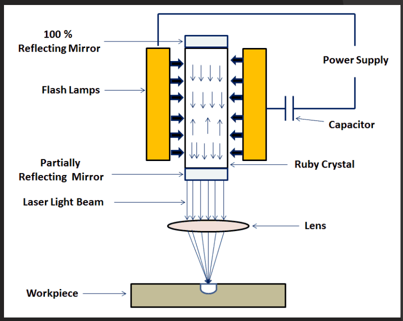


Figure 26: Laser Beam Machining process

-Metal master die needed-
Different methods make use of a metal master die. The disadvantage differ per method, but the common disadvantage is that first a metal master die has to be made, which is not cost nor time efficient. Producing these parts is conventionally done with the use of a CNC machine or with one of the 2D manufacturing methods mentioned previously. Therefore, there is no real advantage for these methods over the traditional (expensive) methods, although it has to be said that milling the positive of the product itself is often quicker, easier and more accurate than milling the negative. Another downside of this method is a form freedom limitation, it is not possible to manufacture cavities or overhangs. As with the 2D manufacturing methods, they could be used when the mould design is build up out of a variety of planar layers.
The methods referred to:

- ElectroChemical Machining (ECM)
- Photo-electro-forming
- Hot-embossing
- Superplastic forming
- Extrusion
- Powder pressing

-Low form freedom-

In all categories there were methods, also previously mentioned, where low form freedom was playing a role in the decision to discontinue. Methods that have been reviewed but would result in too many design limitations are:

- (micro) Bending
- (micro) Forging
- (micro) Deep drawing (figure 27)
- Stamping
- Hydro-forming

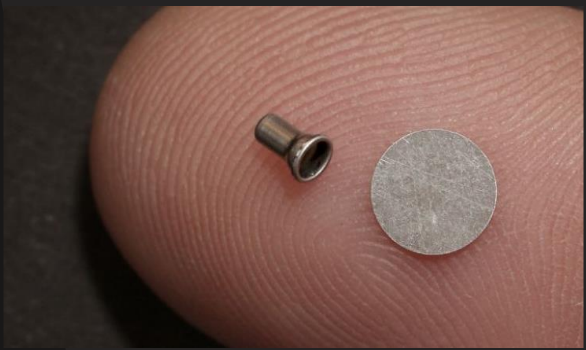


Figure 27: Part produced by micro Deep Drawing

-Ceramic Shell Casting-

A 3D printed shape that is printed in a material that can be burned out without residue is dipped multiple times in a ceramic slurry. This slurry is then baked, removing the casting geometry and hardening out the shell. This is a method used in the prototyping scene, but no proper literature could be found on a micro scale form of this process.

-Additive Manufacturing-

Many additive manufacturing methods are different types of 3D printing. Not all types of 3D printing are applicable for this project, due to low performances on their thermal properties, but mainly their accuracy.

Methods and materials that have been reviewed can be seen in figure 29 (Shahrubudin et al., 2019). The IM team is mainly focussing on optimising 3D printing the moulds with temperature resistant materials like polymers and composites, on their DLP printers (Envisiontec Perfactory, BMF 8K, Asiga Pro 4K). Therefore, the focus won't be on printing plastics since this is already covered and only partly on outsourcing of printing ceramic moulds for that same reason. The results of the team will be taken into the overall evaluation and recommendation of the methods.

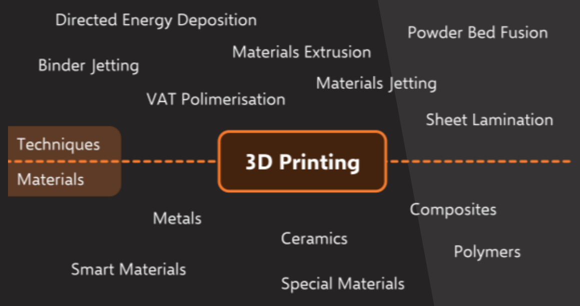


Figure 29: Possible 3D printing methods and materials

The evaluation of additive manufacturing was started with a global research soon followed by a selection in materials. Printing materials that were selected for further research are metal and ceramics due to their thermal resistivity and strength. Moreover, composites were considered, but due the wide variety not fully mapped out.

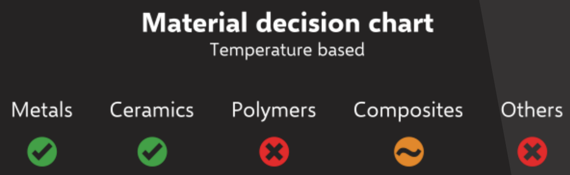


Figure 30: Materials decision chart

Polymers were, as mentioned before, left out of the scope since the IM team was focussing on this. The category "others" is for materials like food, cement, etc.

All printing technologies were reviewed, but mainly on their possibilities to print the selected materials (figure 30). If the technique is capable of this, accuracy was the most important criteria for the technique to be selected as a method to validate. Selected methods are described in the validation part of this research, performances of discarded methods can be seen in appendix I.

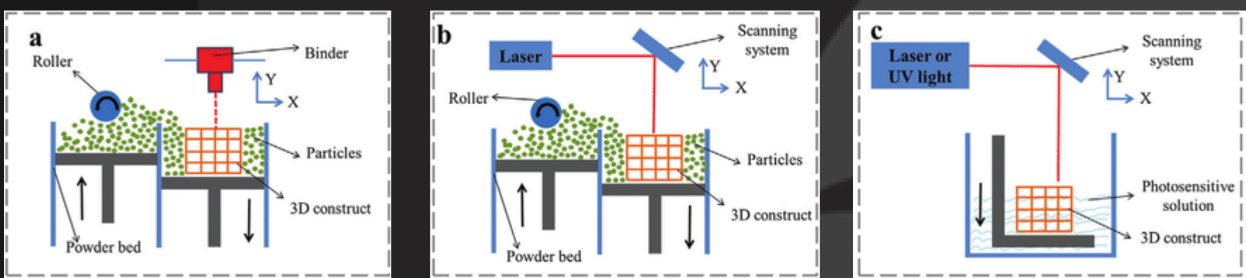


Figure 28: From left to right, Binder Jetting, Powder Bed Fusion and VAT poimerisation

Benchmark – CNC & EDM

Normally, moulds are produced with a combination of CNC machining and Electrical Discharge Machining (EDM) resulting in a very accurate and durable mould. Most commonly, hard tooling is used for high volume production of parts and is used to refer to hardened steel mould. For prototyping, soft tooling is often used. Those moulds are often made of aluminium, but can also be made out of silicone, carbon fibre or fiberglass, depending on what material is injected (Melito, 2022). The mould production at Sonion is for prototypes only, from here on only soft tooling will be considered. Outsourcing mould fabrications to a CNC/EDM company is the current situation for Sonion and therefore the benchmark in this project.

EDM
CNC is considered to be a well-known method and won't be covered in detail in this report. The limitation of the CNC method is the use of round tools, which make it almost impossible for the machine to produce straight corners in cavities. EDM, of which a schematic can be seen in figure 31, is a manufacturing process whereby material is removed from the workpiece by current discharges between two electrodes, one of which in some cases the master die. In this case, a metal shape is pushed into the metal work piece, subtracting the die shape. EDM can also be done with a tiny rod and moveable axis, which can also be seen as a very accurate way of CNC machining.

Cost
When a 1000 pieces are ordered at a professional injection mould manufacturer, most of the cost goes into the production of the part. Because the time and effort put into the production heavily depends on the complexity of the mould, the prices have quite a big range. On average the production of the pieces costs around €15.000, €14.000 on the production of the mould and €1000 on the injection moulding of the parts.

Time
It takes 4-8 weeks for all parts to arrive. This range is so big, again, due to the variation in complexity of the part.

Accuracy
The accuracy these companies are able to provide is satisfactory for all parts, yet obtaining the right properties for parts can be difficult. Once the parts come in, certain dimension could be slightly off, or the fit just doesn't snap as intended. The company then modifies the existing mould, if possible, for around €800 and produces another batch of parts. When a mould can't be modified, a new mould will be produced for which full price has to be paid.

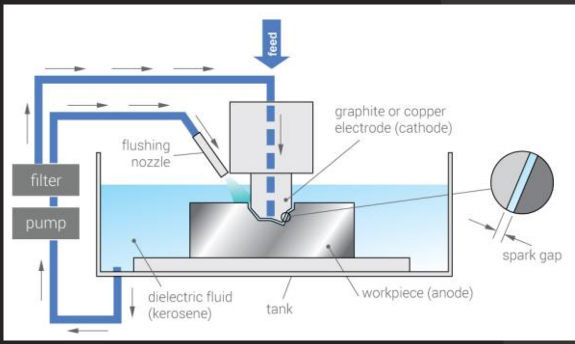


Figure 31: EDM process

In house vs. outsource
It is within the staffs competence to do the manufacturing of the mould in house, question is if it is viable and therefore desirable to do so. The IM team is currently looking into a desktop CNC (figure 32) that costs €15k, but with an xyz tolerance of ±50,8 it probably won't be accurate enough. A 5 axis CNC or EDM machine are easily €100k+, and is therefore considered to be not viable at this point in time. When the demand increases, it is worth to reconsider this judgement.

Figure 32: Pocket NC

Method selection

Methods that have been chosen for further development scored well on most criteria, but more importantly were potentially capable of producing moulds that could resist the melt temperature by a substantial margin. In this chapter the process of the method will be covered and the reason why the method was chosen will be highlighted.

Micro casting *In-house*

The micro casting method is based on the lost wax casting method. In this method, a slurry of investment is casted around a wax model. Once the mould is hardened out, the whole setup is placed in the oven for the wax model to be burned out and the investment to be fully sintered. An overview of this method can be seen in figure 33.

Figure 33: Investment casting process

This is a very old way of casting, but under the right circumstances also useful for casting micro parts (Baltes et al., 2005). Usage of this method might enable Sonion to produce the moulds out of metal, a material category that is capable to coop with the temperature and pressure to which the mould is exposed to in the injection process. The form freedom is as high as that of a 3D printer, since the cast shapes will be printed. Furthermore, with the accurate replication of micro features, an example of which can be seen in figure 34, this method has the potential to be very accurate. Downsides of the method is that the cycle time might be a bit higher compared to the other selected methods and that it is still unclear what the shrinkage behaviour of both the investment as the metal. The shrinkage behaviour has to be uniform for the separate directions.

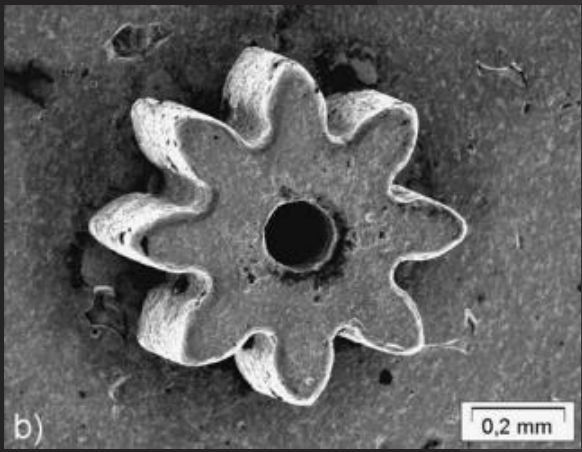


Figure 34: Micro gear casted in aluminium bronze

-Investment-

Conventional investment slurry is most often plaster or phosphate based. These powders are then mixed with a liquid, either distilled water and/or occasionally an expansion liquid to compensate for the shrinkage during the solidification of a specific metal. In order to make the investment more accurate and decrease the surface roughness, a large amount of very fine grained (<10 µm) silica powder can be added to the slurry (Rath et al., 2006). In this situation, the conventional plaster or phosphate powder is merely used as a binder.

-Metal-

There are two main requirements regarding the metal. The melting temperature should be well above 350 °C (one of the criteria) but below 1600 °C, which is approximately the melting point of the silica powder. Furthermore, the flowability of the molten metal is of big impact on the accuracy of the cast. Two types of metal have been identified as promising materials, namely Stabilor G by DeguDent and a specific aluminium bronze alloy (Baumeister et al., 2006).

-Casting-

Two casting methods have been identified that perform well enough to cast on this scale. The old centrifugal casting machine could be able to cast on this scale, but the more modern vacuum/pressure machine has the preference due to a more controlled way of casting.

Powder Injection Moulding (PIM)

In-house

Main problem with the available methods within Sonion is that, although they are able to print the moulds with the right accuracy, the heat deflection temperature of their best material is below the 350 °C it has to withstand. Powder Injection Moulding (PIM) can be done with both ceramic and metal grains and has an injection temperature of around 180 °C, not nearly as high as e.g. APEC 2097 (~330 °C), which makes it well suited for the

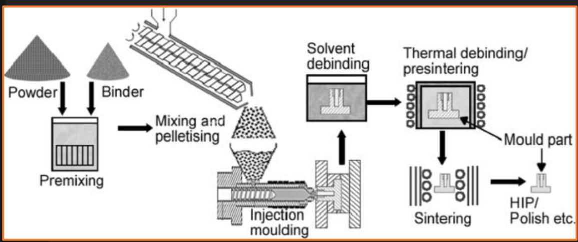


Figure 35: PIM process.

3D printed moulds. The low injection temperature is a result of the combination with a polymeric binder. After the ceramic/binder powder mixture is injected, the so called "green part" has to be debound to take the polymers out of the part. This now solely ceramic "brown part" has to be sintered in order to join all ceramic particles. An overview of this process can be seen in figure 35. During this last step, a shrinkage of ~20% can be expected (Beck et al., 2006). As for the micro casting method, the main advantage of this method is that a ceramic or metal part can be acquired with the form freedom of a 3D printer. Examples of powder injection moulded parts can be seen in figure 36. Due to the different steps in the process, that might involve some additional iteration loops, this is also one of the more labour intense methods.

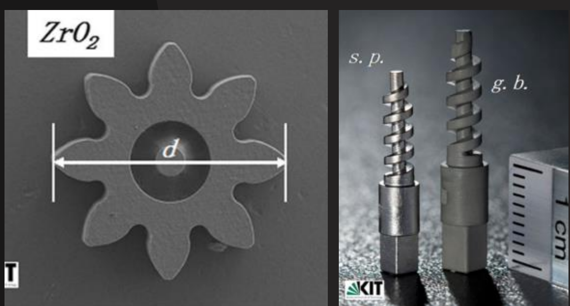


Figure 36: Micro gear, d = 1.5mm & Dynamic thread. (PIM)

Feedstock

For the method's accuracy it is important that the ceramic particles in the powder, the feedstock, are of the right size. The important characteristics of the grains are the particle size, shape, distribution, specific surface area and purity, which have a big impact on the final product (Basir et al., 2020).

Sintering

The sintering process of the brown parts results in a lot of shrinkage of the product. For parts on the meso scale this is very predictable and a common procedure, but for parts in the micro scale this is new territory. However, there are papers that report promising results in this area (Gietzelt et al., 2004).

Ceramic 3D printing

In-house / outsource

Printing of ceramics is a method that combines the technique used in CPIM and light based 3D printing techniques, like StereoLithography (SL), Direct Light Processing (DLP), InkJet Printing (IJP) etc., to acquire the previously mentioned green body (Chen et al., 2019). The slurry of ceramic particles and liquid binder (at room temperature) is solidified by a UV light source which comes often in the form of a laser or a beamer type setup. From this point on, the procedure is the same as with injection moulding. This method has the same advantages as CPIM but is easier to execute, which results in a less labour intense process but also in a less accurate result.

Figure 37: Frauenkirche, height = 16.6 mm. (DMLS)

Direct Metal micro Laser Sintering

Outsource

Printing metal can be done in a similar way as printing ceramics, with the use of a binder that emulsifies the grains, but it can also be done with only the fine grained powder and a laser. The laser fuses the grains into a solid layer, after which a new layer of powder is laid down on the solidified layer for a new layer to be sintered (Venkatesh & Nandini, 2013). Although this method is known for its high surface roughness, developments in recent years have established a form of DMLS that is also usable on a micro scale with a. surface roughness of 3-4 µm without post processing. This is partly due to the decrease in grain size and laser size, which also enables the production of features on a micro scale (figure 37).

Zirconium Milling

Outsource

This method uses the traditional 5-axis CNC milling technique, but uses it on tightly squeezed zirconium powder, a brick of green state zirconium. This can be milled easier and possibly with more precision. As with all ceramics, these parts have to be sintered together after milling. Standard dental milling machines are not accurate enough for Sonion's applications, but the best performing dental CNC machine, a Zirkonzahn CNC (figure 38), might be capable of producing parts with the right accuracy. Most denture labs provide services to produce and deliver a part in 3 to 4 days for around 100 euros for a mould halve, making this a potential outsourcing method. This makes it a very attractive method because it has, taken into account that it is outsourced, a low cycle time for a low price. Biggest obstacle for this method is the production of small features which will be the first aspect to be investigated.

Figure 38: Zirkonzahn CNC

Electrochemical Fabrication

Outsource

Additive Electrochemical micro-Manufacturing (AECM) comprises multiple methods working all along the same principles. Electochemical fabrication works following the principle of cathode electrochemical deposition. In an aqueous electrolyte, metal ions are reduced to metal atoms which are driven to the cathode by an external electric field (Xinchao et al., 2021). A division can be made between mask based and mask-less fabrication, both can be seen in figure 39. In the mask based variant, the flow freedom of the atoms is limited by a mask. In the mask-less variant, the anode is substantially reduced in size, resulting in a very predictable and accurate flow of atoms. This anode can then be moved by a nano stage. Both methods are capable of printing on a nano scale, as can be seen in figure 40.

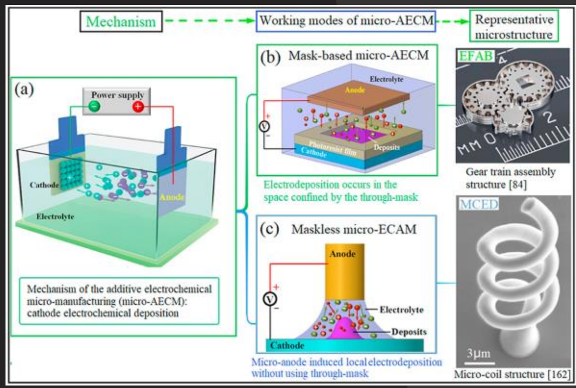


Figure 39: AECM; mask based and mask-less

Due to the very high accuracy this method offers in combination with the possibility of printing metal, this method is in theory very capable of producing the moulds very accurately while complying with all other requirements. The disadvantage of this method is the restriction in build volume.

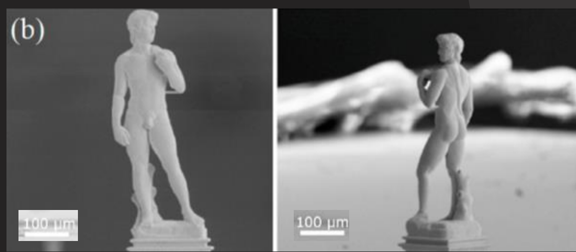


Figure 40: Copper Michelangelo's David (Fluid FM electrodeposition)

Measuring performances

A matrix is constructed (figure 41, next page) that visualises the estimations of each of the chosen technologies that are deemed feasible and viable. Because the IM team is also working with such a matrix, I took the lead and added the methods that are developed in the IM team too (CNC, 3D printing plastic/addifab). The full matrix, including the methods of the IM team, can be found in appendix III. Estimations for all criteria are based on the knowledge at the end of the research phase, so before the validation phase. Therefore, it was not possible to make a well-founded estimation for many criteria which is visualised in the decision matrix by a question mark.
This matrix is used keep track of the current status of each method and to make decisions accordingly, during the validation phase it was a living document that was continuously updated. In the conclusion phase, the matrix can be seen completed up to the point a good decision can be made.

Decision matrix

Down below, a simplified visualisation can be found that shows the estimated performance of each method. A green check mark means it is estimated the method passes the criteria, an orange tilde means the method might not pass the criteria and a question mark is used when there is too little information to give a good estimation. A small symbol in the right top corner of a symbol, means the method is leaning towards that symbol.

To clarify the matrix, some of the most important aspects will be categorised and covered.

- Direct printing -
The methods Electrochemical Fabrication and Direct Metal Laser Sintering were joined because they fall in the same category and resultingly produce very similar parts, but with different techniques. Therefore, most commercially available metal printing methods that approach the required accuracy are covered in the validation phase.

- Ceramics -
Three methods in the chart, PIM, Ceramic 3D printing and zirconium milling, can be used to acquire a ceramic mould. For the first two, the method can also be used to produce a metal part by swapping the ceramic grains my metal grains. Since metal has the preference, due to the brittleness of ceramics and the higher thermal conductivity of metal which is expected to be more suitable for this application, it is preferred for the method to produce a metal part. For PIM this is possible due to the wide availability, but this type of grain resin printing ceramics are more available. Moreover, ceramics remain a promising material and therefore should be included in this research.

- Temperature criteria -
From the range of criteria, the temperature was an absolute demand and therefore has to be met by all criteria. Therefore, all methods should withstand a melt injection temperature 350 °C with ease and preferably up to 500 °C (as mentioned on page 12).

- Ease of execution -
By looking at the ease of execution criteria, the difference between an in-house method and a method that is aimed to be outsourced can be seen. When a method is outsourced, the ease of execution is deemed easy since no labour needs to be done to acquire the mould.

- Surface roughness -
Making an estimation for the surface roughness was difficult at this point because there was a lack of information for each method and because within the IM team it is unclear what the highest tolerated roughness can be. It should be kept low and then tested in the moulding process itself. Besides, there are possibilities to improve the roughness although the mould has to be designed for this post processing step.

	Micro casting	Powder Injection Moulding	Ceramic 3D printing	Zirconium milling	Direct Metal Printing
Temperature	✓	✓	✓	✓	✓
Accuracy	?	?	✓ (?)	?	✓ (?)
Iteration time	~	~	✓	✓	~
Cost	?	?	?	✓	~
Tool life	✓	✓	?	?	✓
Form freedom	✓	✓	✓	~	✓
Ease of execution	?	~ (?)	✓	✓	✓
Surface roughness	?	?	?	? (✓)	?

Figure 41: Decision matrix, early estimations for most criteria

Validation

Metal 3D printing
Zirconium milling
Ceramic 3D printing
Micro Casting
Ceramic Pressing
Powder Injection Moulding

In the validation part, the chosen methods will be further evaluated and put to the test. Several techniques have been applied in order to do this, since not all tests could be done in-house. Some methods have been examined solely by contacting companies that are experience with the methods technology. Others have been examined in a hybrid form; in-house testing with the help of experts.

To validate efficiently, the focus was to test aspects of the test that were most likely to kill the method. Identifying these aspects had already been done during the research and was visualised in the decision matrix.

For each method, the distinction has to be made between in-house production and outsourcing. Criteria that heavily depend on this distinction are the price, the iteration time and the ease of execution.

Direct Metal 3D printing

Validation

Validating the metal 3D printing method is done in collaboration with other companies. Their estimations of the producibility of the reference parts was leading in the decision making for this method.

Metal printing methods

Withing the micro metal additive manufacturing industry, a distinction can be made between thermal based additive manufacturing methods and additive electrochemical manufacturing (figure 42) . The more commonly known and more often used thermal based method works on the principle of heating metal grains, most often with a laser or an electron beam, to connect the individual grains and so creating a product. The more advanced and therefore commercially less frequently used method of electrochemical manufacturing works, as mentioned before, in an aqueous electrolyte environment. Metal ions are reduced to metal atoms which are driven to the cathode by an external electric field (Xinchao et al., 2021), forming the metal part.

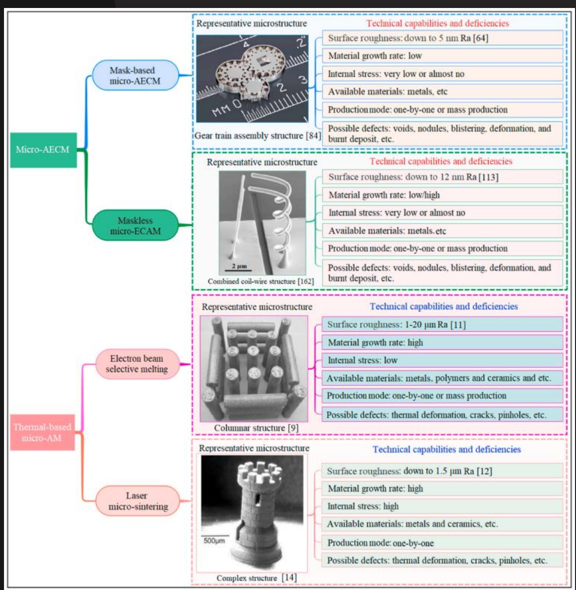


Figure 42: Micro additive manufacturing diagram

Besides these two main methods there is a 3rd printing method, that is covered from page 33 onwards in the ceramic printing paragraph. It is not considered in this paragraph because metal is not printed directly but with a polymeric binder.

Mask based & maskless AECM

Both these methods work on the same principle, the difference being the start and end point the electrons travel from and to.

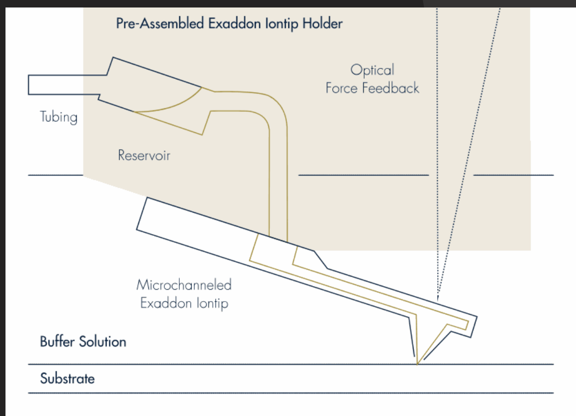


Figure 43: Material dispensing method maskless AECM

For the maskless form, a needle is connected to an XYZ nano stage that moves a small printing nozzle through the building volume, a bath with an electrolyte liquid. A liquid containing metal ions is ejected through a micro channel in the nozzle with a flow as low as a few femtoliters per second. Once the liquid metal ions hit the substrate or print plate, the ions are electrodeposited into solid metal atoms. Instead of the print being build up of layers, this print is build up of blocks (< 1 µm^3) called voxels. The printer senses when a block is "filled" by the optical force feedback measured on the tip of the nozzle arm (Exaddon)(figure 43&44).

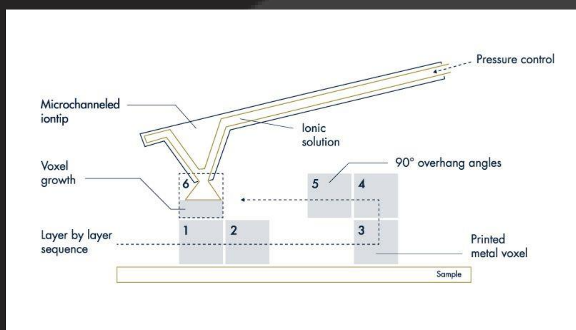


Figure 44: Printing voxel structure maskless AECM

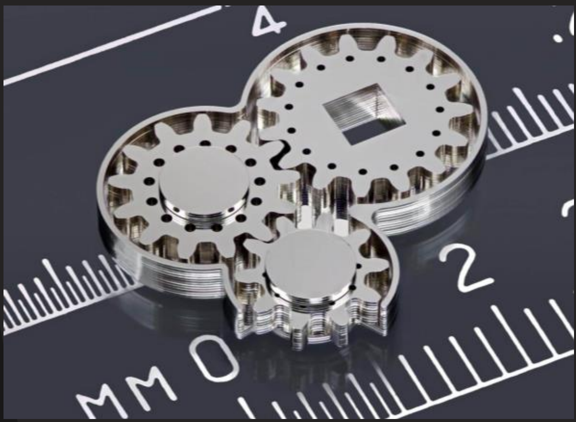


Figure 45: Parts produced by mask based AECM

The mask based AECM method works with a photo resistant pattern that only allows the electrodeposition to happen in locations that is not blocked by the pattern, which is visualised in figure 39 (page 28). This results in a print build up of layers that are extremely flat, planar and of accurate thickness (±2 µm), as can be seen in figure 45 (MicroFabrica).

Current commercial performances

The performances of the largest companies in the metal AM field have been reviewed (figure 46) and occasionally contacted to check if their production standards meet Sonion's requirements. The difference in accuracy between the companies can

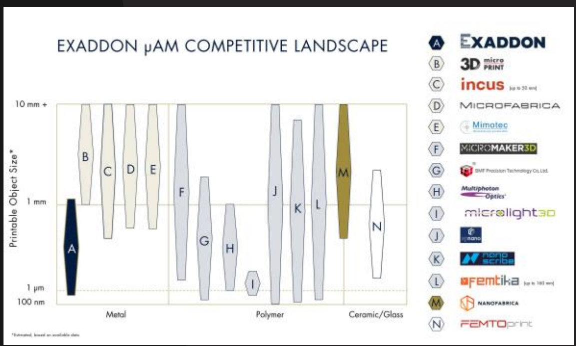


Figure 46: Competitive landscape micro Additive Manufacturing

be related to the technology that is used by the particular company. Companies that are able to produce parts in the size range that is required (tens of millimetres) use a thermal based method like DMLS and work with tolerances according to DIN ISO 2768 (MicroPRINT Gmbh) for parts like the RIC insert. This comes down to tolerances ranging from ± 0.05 mm to ±0.1 mm for nominal lengths from 0.5 – 6 mm to 6 – 30 mm.

When mask based electrochemical manufacturing is used the tolerances meet, or are actually below, the requirements of Sonion. This steep increase of accuracy comes at the expense of the build volume. The build area of this method is sufficient, a circle of 100mm, yet the build height is only 1 mm. Taller parts can be made by stacking prints and welding them together, but this would make the process even more expensive and time consuming. The build time already is, due to the production of the photomasks, several weeks for a single part without stacking and welding.

For maskless micro-AECM, the build volume is often around the 1 mm x 1 mm x 1mm which is far below Sonion's requirements.

	Accuracy	Build volume	Build time
Thermal based	✗ ±50 µm	✓ 60x60x60 mm^3	✓ Hours
Mask-based AECM	✓ 1 mm slices	~ 1 mm slices	✗ Weeks
Maskless AECM	✓ ±2 µm	✗ 1 mm^3	

Figure 47: Metal additive manufacturing decision matrix

Conclusion

After reviewing the performances of the main providers of metal additive manufactured parts by contacting them and additional online research, it became clear that this industry is not suited (yet) for Sonion's applications. A balance between the right build volume and the right accuracy has to be found for this method to be profitable (figure 47).

Besides the 2 main methods covered in this paragraph, there is one more method that allows to print metal. This will be covered in ceramic 3D printing, a technique that is also used to print metal.

Figure 48: MicroFabrica print scale reference

Ceramic 3D printing

Method

Validation of ceramic printing was done by reviewing the capabilities of all ceramic printing techniques and services. Due to the brittleness of ceramics, the mould will fall just inside the mother mould, so the clamping force of the machine on the insert is minimised which might result in fleshing around the sprue.

Printing of ceramics

For this method, commonly used, printers that work on the principle of curing a photosensitive resin with a form of (UV) light like SLA and DLP, are used in combination with a fine grain ceramic or metal powder. The method simply works by mixing finely grained ceramics with the photosensitive resin, that is later in the process sintered out of the object in an oven. A process that is also possible for fine grained metal, but due to the more widely available ceramic printing technique this was chosen to pursue. Printing metal with this method is less available because the previously mentioned metal printing methods SLS and AECM are preferred in the industry (Incus) due to a process that involves less steps and therefore is cheaper. The resolution of these printers is determined by either the diameter of the beam of light or the pixel size of the screen used to block light from the light source behind it. In the sintering step, the object shrinks between 15-30% which can be used as an advantage only if the shrinkage is uniformly. All dimensions shrink a bit, resulting in a decrease in radii size and printing tolerance by the shrinkage percentage. A factor that has to be taken into account for this method is the fact that it will never reach a state of 100% solidity, which also influences the porosity of the outer surface. Also, the shrinkage has to be uniform else warpage will occur. Most shrinkage takes place in the sintering phase, not in the debinding phase (Lithoz). For injection moulding, the inner surface of the mould can't exceed a certain roughness for the part to be removable at the end of an injection cycle and to have a satisfactory quality.

Validation

The intentions were to obtain a sample from a company that is experienced in printing ceramics. For the printers at Sonion the ceramic material is commercially available as well, but because there is no oven available capable of programmed heating (heating along a profile) in house testing was not possible. Furthermore, the experience of a specialised company would add to the result of the print which would therefore be more representable for the capabilities of this technique.

Practical possibilities

Because of this method's promising features, a market analysis has been done of all available, well established, ceramic 3D printers (table 2). The two most suitable companies were Lithoz, with the most accurate printer, and Admatec. At first the focus was on Admatec due to its Dutch origin and therefore its practical advantages. Because

3DCERAM	LITHOZ	ADMATEC	TETHON 3D	voxeljet	Desktop Metal	XJET
~	✓	~	✗	✗	~	✗
~60 µm laser diameter	25 µm pixel resolution	40 µm pixel resolution	57 µm pixel size	0.3 mm layer height	30 µm voxels	50 ±µm tolerance
SLA	DLP	DLP	DLP	Binder jetting	Binder jetting	Material jetting

Table 2: Commercially available ceramic printers and their performance

Admatect is also on Sonion's radar, it was not possible to explore their capabilities in a similar way as done with companies in other methods without interfering with the relation between Sonion and Admatec. Therefore, the focus was shifted to Lithoz, although they do not provide a printing service.

Digital Light Processing

This method makes use of a beamer like setup and a mirror (figure 49). For some DLP printers, the light source is fitted with a special DLP light but, others have a light build up of many LEDs. The LED source can be seen as a grid of LEDs that are turned on or off individually resulting in difficulties

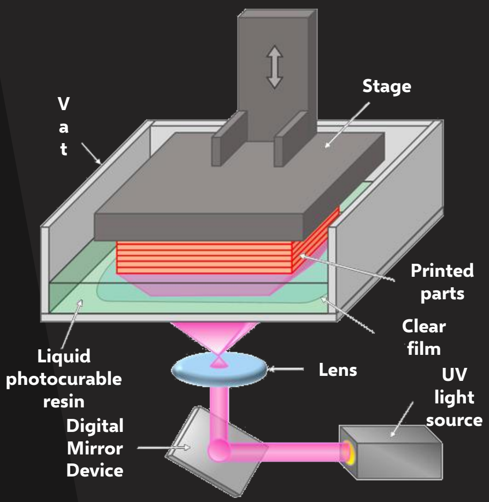


Figure 49: Direct Light Processing schematic

for rounded corners and high tolerances. The grid won't be visible with very straight corners, but can be seen as a grid with rounded squares. The tolerance of a DLP printer is related to the pixel size in the light source. As an LED can only be on or off, part of the tolerance is the difference between de LED step and the actual dimension. As an example, one of the most advanced ceramic

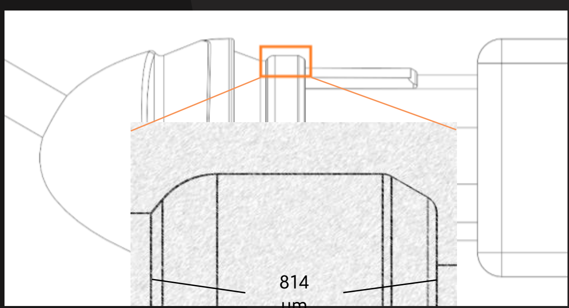


Figure 50: Reference part for grid visualisation

printers is the Cerafab system s25 by Lithoz with a pixel resolution of 30 µm (at a minimum layer height of 10 µm) which therefore can have an addition of ±29,9 µm on to the ±20 µm tolerance of the printer. It is possible to design for this type of 3D printing by making sure dimensions are multiples of the pixel resolution to eliminate this addition to the tolerance. According to Lithoz, when the design has been adapted, a tolerance of ±20 µm can be reached and fillets can be rounded by making slight changes to each layer. When the pixel size is not taken into account, the influence of such a grid on one layer of a part (figure 50) of the shape of the mould can be seen in figure 51. However, the parts go after printing into the sinter oven, where 15–30% of shrinkage occurs. Along

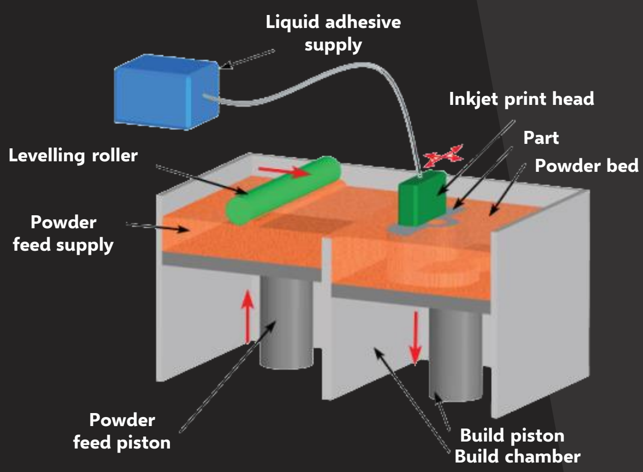


Figure 51: Binder jetting schematic

with all dimensions, it decreases the pixel resolution and tolerance by this amount as well. This results in the ±20 µm which makes this an interesting method to produce the moulds.

Binder jetting

Binder jetting is a form of powder bed printing, where a new layer of powder covers the print bed

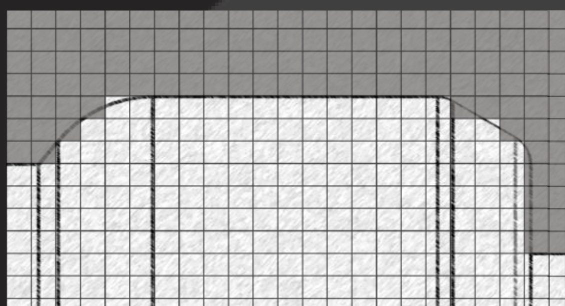


Figure 52: LED grid visualisation (40µm resolution)

or the printed part (figure 51). Then, a liquid binder is dropped on specific parts of the powder bed, where a UV light will solidify the binder. After printing, the binder has to be sintered out of the printed result. Because of the usage of liquid droplets that are dropped onto the powder, this technique is more difficult to control limiting the accuracy of this method. The most accurate printer is able to print voxels, cube approximations, of 30x30x30 µm^3.

Material jetting
Similar to printing methods that use a bath of resin combined with fine grained ceramic powder, material jetting or Drop on Demand (DoD) printing is done by dropping small droplets in specific location. Two materials are used during printing; the material that the part is be made of, which is in this case a resin with ceramic grains, and a support material. After one layer of drops, the layer is solidified by a UV light.

Nonspecific printers
Resins have been created for printers that are not specifically made for ceramic printing, like for example by Formlabs, to use in their printers. Printing with these resins in standard printers does not give stable and reliable results (Truxova et al., 2020) and are therefore not taken into account in the market analysis.

Validation
Initially the aim was to validate this method by requesting a sample that could be reviewed at the facility in Hoofddorp. Binder jetting and material jetting were not accurate enough and therefore discarded. After having contact with an engineer from Lithoz on the performance of their printers, the conclusion was that their method would be able to produce the parts with the right tolerances (±20-±40 µm). However, one of the reasons for their accurate results is their sintering time of 2 week. Although the price was sufficiently low at Steinbach, a production company that was recommended by Lithoz, where one side of the mould body could be produced for €400, the time it would take to produce this was 4 weeks + 2 weeks for every iterative step needed to obtain the ±20 µm tolerance for certain dimensions.

Conclusion
After several discussions within the IM team and supervisors, it was decided to discontinue research for this method due to the previously mentioned high cycle time (table 3). This cycle time does not allow quick iterations and therefore hinders the prototyping too much, resulting in a cost increase as well. Furthermore, it is still unclear whether ceramics are well suited as a material for the moulds due to its brittleness.

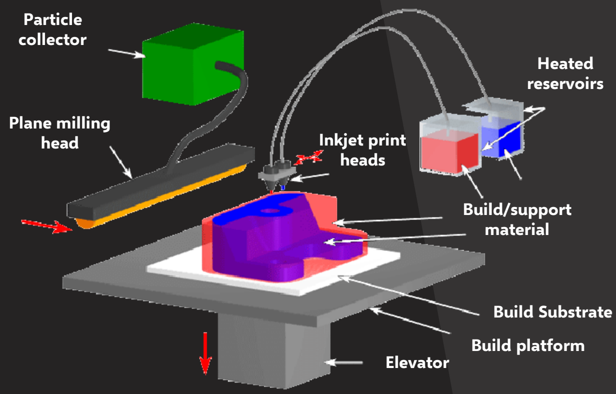


Figure 53: Material jetting schematic

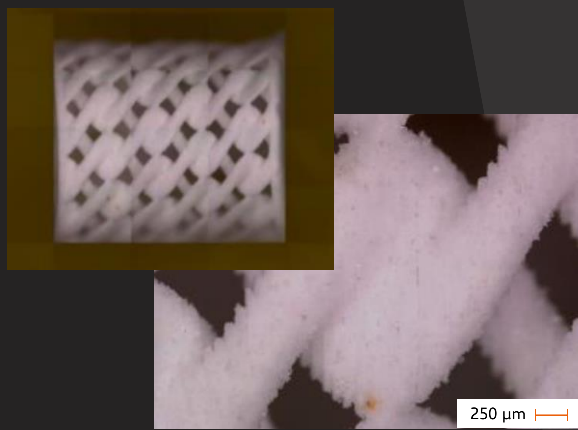


Figure 54: Ceramic part printed by a DLP printer

Temperature	✓	Sufficient
Accuracy	✓	±20 µm
Iteration time	✗✗	6+ weeks
Cost	✓✓	~€800
Tool life	?	
Form freedom	✓	
Ease of execution	✓	

Table 3: Material jetting performance

Zirconium Milling
Validation

Milling of ceramics had been chosen as one of the methods to pursue because it scored well on the price and time criteria. This method is mainly meant to be outsourced and for parts similar to the RIC insert in size, but if proven to be up to standards could also be used in house.

Validation

To validate this method, first the most accurate CNC machine had to be identified. The brand that offers these is Zirkonzahn, an Italian brand that strives for technological optimisation by making there own milling burs, optimised for their ceramics. In order to map out the possibilities of this CNC machine for the production of the mould, companies that work with a Zirkonzahn have been contacted and possibilities have been discussed with the R&D of Zirkonzahn.

Practical possibilities

Originally, this method only works if the production can be outsourced in a quick and inexpensive manner but with the right accuracy. Therefore, a visit was paid to SmileDesign, a company that offers a service like this. Having two different Zirkonzahn machines and a compatible oven, this company is as well-equipped as possible to mill ceramics.
The initial motivation for selecting this method is that of other, more traditional, zirconium CNC companies offering a 3-day delivery guarantee for ~€100,-. It was expected that this more accurate way of milling would come with a price increase. After the whole method was explained and shown to some members of the SmileDesign staff and the RIC insert was shown, it became clear that many angles could probably not be made with the CNC machine. The company uses the 3 mm milling burs provided by Zirkonzahn, in their range of burs a medium sized milling bur, which would result in inner edges having at least a 1.5 mm radius. Working with smaller burs (down to 0.3mm diameter) can be done since these are offered too at Zirkonzahn, but that would increase the price rapidly due to the time-consuming trial and error process it would likely result in. Products of similar size as a single mould halve already cost €3000, with the added expenses of the trial-and-error procedure it will be even more expensive. Since two mould halves and possibly inserts have to be produced, outsourcing the production of the moulds in this way is not deemed feasible.


Figure 55: Laboratory Smile Design


Figure 56: Part produced by a Zirkonzahn machine

Theoretical possibilities

To see if the Zirkonzahn machine is technically capable of producing the mould, the R&D department of Zirkonzahn was asked to estimate the possibilities in the most optimal case. To avoid having to sign an NDA, a different sample part was send. This is an already released RIC insert, therefore not secret but very similar to the RIC insert reference part. The biggest difference is the pillar in the right top corner of the cavity (figure 57), which is missing in the RIC insert reference part. However, this difference doesn't influence the usefulness of the analysis in a negative way, since it adds an extra difficulty while most parts of the shape are very similar.

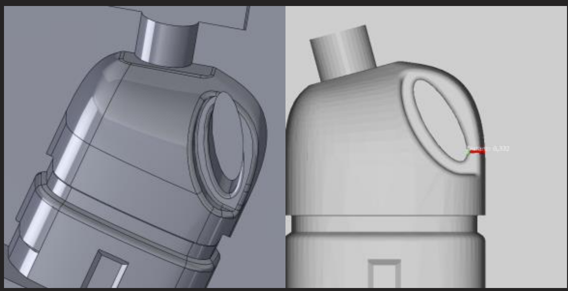


Figure 57: Sample part (left) and gap between pillar and wall (right)

The smallest milling bur Zirkonzahn offers is 0,3 mm while the most narrow gap, between the pillar and wall (figure 57), is 0.332 mm. This gap should at least be 0.4/0.5 mm, so the design should have been adapted for this. Of course, this pillars is not present in the chosen RIC insert reference part but it does say a lot about the free from ability of the method.

As with any form of milling, straight inner corners can't be produced, which is also the case for this instance. In figure 58 it can be seen what can and can't be milled. The moss/grass green parts can be milled, but the lime green and blue parts will only be milled partly or not at all.

Figure 58: Milling simulation result (picture: Zirkonzahn)

Looking at the actual reference part with the knowledge of the Zirkonzahn analysis, it becomes clear that at least the corners circled red in figure 60 can't be milled. It is suggested by the R&D department to make some redesigns that would make it possible to mill but, keeping in mind that snap fits have to be injection moulded, this method doesn't seem fit for Sonion's applications.

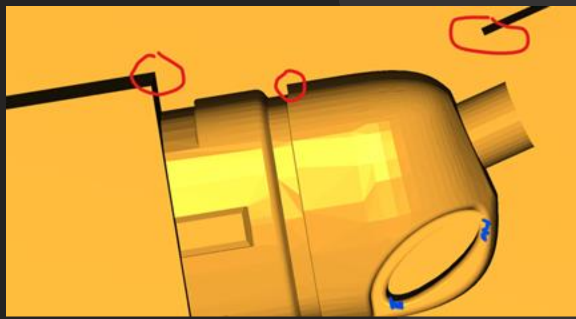


Figure 59: Corners that can't be milled (picture Zirkonzahn)

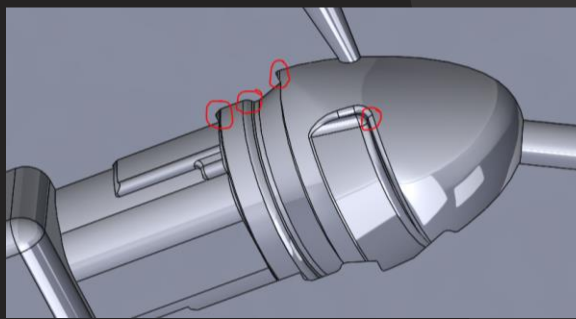


Figure 60: Corresponding inner corners on RIC insert

Conclusion

The cost of this method was initially estimated less than it turns out to be due to the heavy increase in price when a higher accuracy is reached. The method would still be slightly cheaper than producing the mould with soft tooling. However, the maximum accuracy does not reach the requirement. For these two reasons the method has been discarded. In table 4 an overview of the performance of this method can be seen.

Temperature	✓	Sufficient
Accuracy	✗✗	0.3 milling bur
Iteration time	✓✓	3-5 days
Cost	~	€6000+
Tool life	✓	
Form freedom	~	
Ease of execution	✓	

Table 4: Ceramic milling performance

Micro Casting
Method

The micro casting method is one that needs more testing than others due to its unconventionality. An industry that approaches micro casting the most is that of dentistry and jewelry. Although this field is heavily focussed on the accuracy of the casted parts, the approach is not as scientific as is required for Sonion. For example, exact tolerances of results are often unknown. A part is a finished when it fits and if it doesn't, small modifications to the part are made by hand.

The method
Micro casting is based on the lost wax technique, which originates back to 4500 B.C., used to duplicate gold artefacts. A temperature resistant investment is casted around a wax model. After hardening out, this body is placed in an oven to sinter while the wax pours out of the mould or vaporises. Then, the metal is poured into this mould, often while it is still at the sintering temperature. After casting, the mould is shattered and the casts are ready for post processing. This process is well suited for objects in the macro scale and requires post processing. Other then that it is a labour intensive way of creating a metal part.

In-depth research
A series of studies has been conducted on different aspects of this method to make it applicable for micro scale production. Micro parts have low tolerances and are therefore not fit for most post processing techniques. In these studies, characteristics like surface roughness, investment removability, cast materials, flow length, accuracy and strength of the investment are well covered. An important aspect that is not covered as well as needed are the tolerances of this method. In this research, a fine grained quartz powder filler is added to a gypsum plaster binder to increase the accuracy and to make it more temperature resistant. This way, metals can be casted that replicate shapes more accurately but also have a higher melting point, which prevents the usage of stand alone plaster which decomposes above 750 °C (Baumeister et al., 2006).

Initial testing
Before arranging to cast metal in a vacuum/ pressure casting machine, some tests had to be conducted to proof the method works and is accurate enough to pursue. A plan was made with test steps that have to be completed successfully before continuing to the next step (figure 61). All testing had to be done without professional equipment, so some experimenting was necessary before obtaining reliable results. The results of these experiments can be read in appendix IV.a.

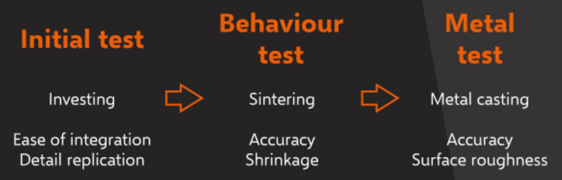


Figure 61: Test procedure micro casting

Investment process test aim
To ensure no time is wasted on a method, the tests inside the scope are aimed to eliminate the method. Therefore, critical criteria for a specific method are targeted during the testing phase. In case of micro casting the critical criteria are:

- **Accuracy**: The ability of the method to copy the original, 3D printed, shape.
- **Ease of integration**: How difficult is it to cast and sinter the investment?
- **Iteration time:** The time it takes to invest and cast one mould half.

Factors outside the scope are expected to be of a minor influence on the testing results and assumed to be absent when all proper tools and materials are used, in case the method will be integrated.

- **Complete removal of bubbles**: The removal of bubbles should be realisable when tools like a vibrating plate inside a vacuum chambre or a vacuum mixer are at hand.
- **Full optimisation casting process:** Due to time restrictions, it is not expected to reach an optimal recipe for the casting method. When results are good enough, the focus will shift to validating the metal casting step.
- **Removability casted shape:** During the first parts of the testing phase, the usage of a castable wax resin was not at disposal. Therefore, the 3D printed cast shape had to be physically removed from the cast, resulting in parts to break or come off.

Investment behavior test: accuracy & shrinkage

Checking the ease of integration has partly been done in the initial test, mentioned on the previous page. Since there was no real reason during these steps to kill the method, it was decided to carry on by mapping if investment can be done accurately enough. The final setup of the initial test is used for the acquisition of results in this chapter. First, the shrinkage behaviour will be covered, after which the second part will be devoted to the repeatability of the investing process.

In order to see if the dimensional differences are uniform and predictable, the X and Y coordinates have been measured on a Mitutoyo measuring microscope. This was done to make sure that the method is able to produce a mould that is accurate enough. If the method wouldn't be accurate enough, no time is wasted on looking for a test facility. To see the variations between each step in the process, measurements of the 3D printed cast shape, the dried cast and the sintered cast have been made.

Shrinkage

While processing the results of the analysis it was evident that the measurements made on the dried cast had a systematic error. After correcting the coordinates by translation, which was necessary due to misalignment, the results were analysed. On average, the absolute difference between the cast shape and the sintered cast is 0.020 mm and 0.023 mm for x and y respectively. Apart from some peaks of up to 0.06 mm, likely due to measuring errors, most values are well below the 0.3 mm. All deviation can be seen in the table 5 and the plot in figure 66. Other patterns in deviations, like for example a continuous increase in values or a correlation between X and Y could not be found. Visuals of the deviation can be found in appendix IV.b.

	A		B		C	
Difference	X	Y	X	Y	X	Y
3D - Cast	-0,034	0,097	-0,094	0,078	-0,072	0,048
Cast - Sintered	0,070	-0,071	0,082	-0,034	0,053	-0,059
CastC - Sintered	-0,001	-0,017	0,011	0,020	-0,017	-0,005
3D - Sintered	0,036	0,026	-0,012	0,044	-0,019	-0,011

	D		E		F	
Difference	X	Y	X	Y	X	Y
3D - Cast	-0,067	0,061	-0,041	0,079	-0,100	0,126
Cast - Sintered	0,094	-0,051	0,025	-0,065	0,100	-0,112
CastC - Sintered	0,023	0,004	-0,046	-0,011	0,029	-0,058
3D - Sintered	0,027	0,010	-0,016	0,014	0,000	0,014

	G		H		I	
Difference	X	Y	X	Y	X	Y
3D - Cast	-0,098	0,029	-0,042	0,081	-0,102	0,048
Cast - Sintered	0,032	-0,020	0,058	-0,049	0,122	-0,028
CastC - Sintered	-0,038	0,034	-0,013	0,005	0,051	0,026
3D - Sintered	-0,066	0,009	0,016	0,032	0,020	0,020

Table 5: Coordinates of each state per point

Depth analysis

The three phases of the cast have also been reviewed with a smartscope, the InfiniteFocus by Alicona. This device makes a height map of products that are placed inside. Aim of the test is to see if the top of the extruding part might deform more than parts of the cast that are better supported due to it being placed face up in the oven. The height has been measured in exactly the same region for all 3 stages, one of those scans can be seen in figure. At the top of the dome, an air bubble can be seen. This was not of influence on the testing result, as the reference point was determined to be on the cylinder next to it. The

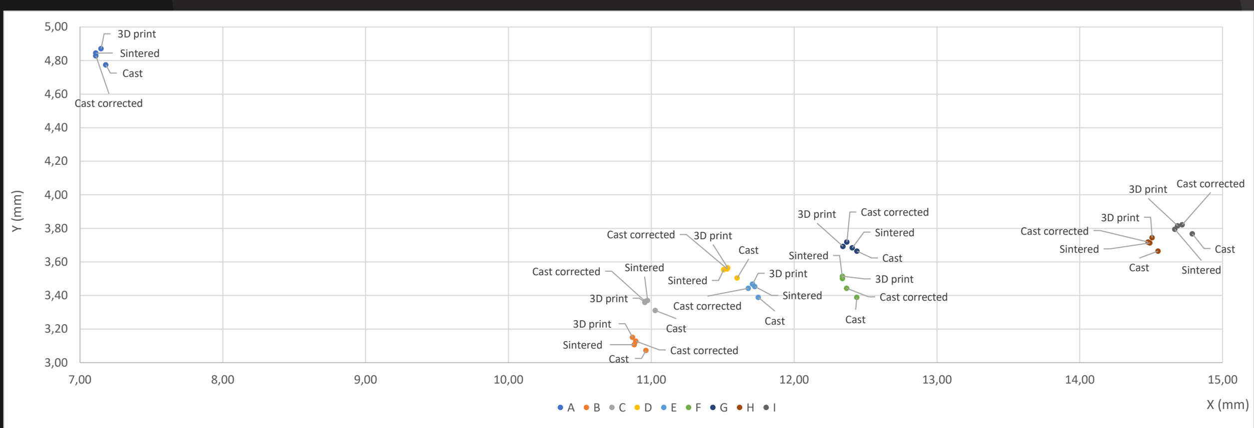


Figure 61: XY analysis plot of the 3D printed cast shape, the dried cast and the sintered cast

height of the 3D print at the reference point was 2.0758 mm and the same point on the sintered cast was 2.0690 mm, which results in a difference of only 6.8 µm (figure 64). Since this measurement is obtained more accurate than the XY data, this is valued higher with respect to shrinkage. The dried cast was higher (13.9 µm) and had a bigger radius (+1.8 µm). The software of the Smartscope also had a tool that measures the radius of the section view. A radius could be formed with the software, showing that the (top of the) cylindrical shape had not sagged or deformed in any significant way.

It can be concluded that the shrinkage behaviour of the investment does not deform the mould in a way that would make the metal cast inaccurate. The exploration of this method was continued by an analysis of the repeatability of investing.

Accuracy

Besides the effect of the shrinkage behaviour of the cast on the geometrical accuracy, the repeatability of casting process should be investigated. It is important for the casts to be accurate and therefore behave in a similar way constantly for the process to be repeatable.
In order to validate if this is the case, a total of 5 sintered casts have been made using the same casting shape. After these casts were dried and sintered, the geometry was analysed with the smart scope. No depth analysis has been conducted due to a lack of time, but previous result doesn't show any inconsistencies. In figure 68, the measured points are plotted of one side of the top surface of the cavity. Details can be found in appendix IV.b. The average absolute deviation between the points of each sample is 10 µm. Concluding, the method is deemed repeatable enough to continue investigations and see how accurately metal parts can be produced.

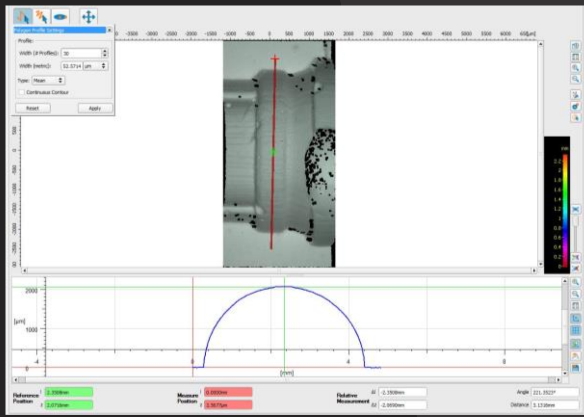


Figure 63: Sectional height analysis

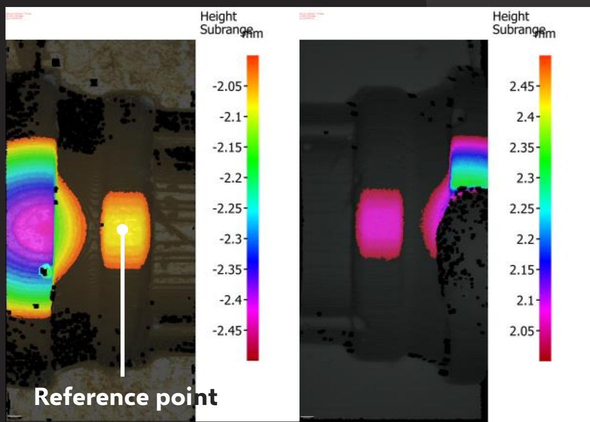


Figure 64: Detailed height profile cast shape (left) & sintered cast (right)

In collaboration with de Vaal Creaties it was possible to cast samples of the RIC insert to analyse the geometrical accuracy. In this test, the result of the casting process of de Vaal Creaties was compared to casting the moulds prepared following the process earlier described. Both moulds are casted with a vacuum/pressure casting machine by Lukacast, provided by de Vaal Creaties.

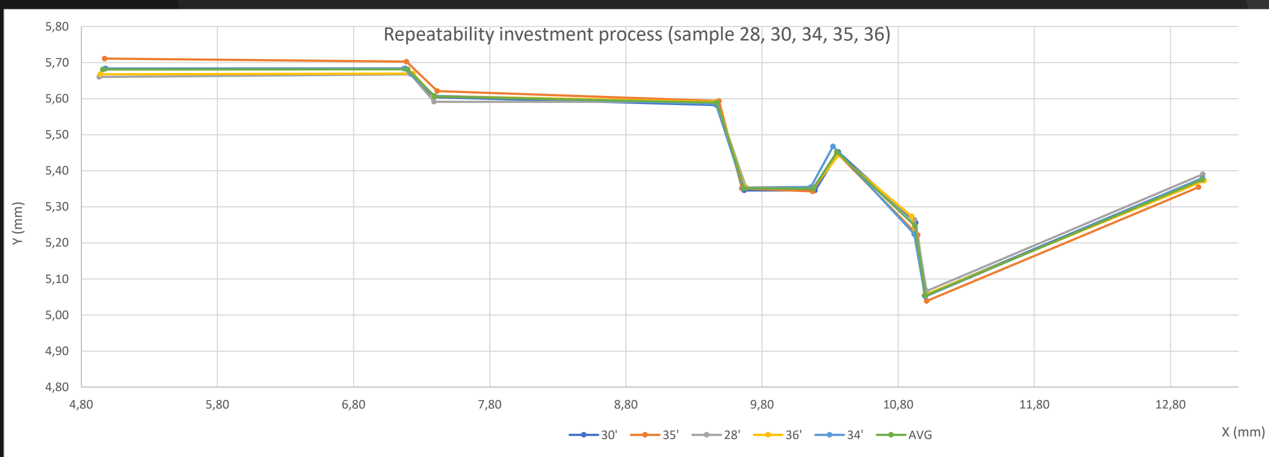


Figure 62: Measured point of the sintered cast to test the repeatability of the method

Micro Casting

Metal casting test results

Method

Before casting, moulds were made and sintered the same way as in testing with. The main difference was the usage of 3D printed wax cast shapes and the use of a casting ring, configuration can be seen in figure 65. The investment is poured

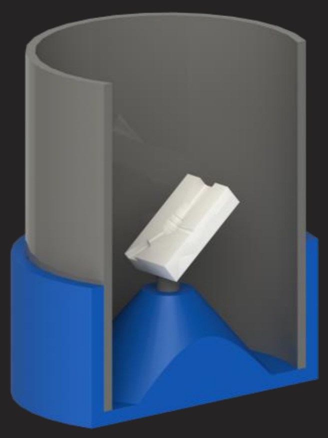


Figure 65: Investment configuration metal casting

and scooped in from above, while the investment inside is vibrated shaking the ring by hand and tapping the spatula against the bottom to remove air bubbles. In this phase, a 50/50 ratio of quartz/plaster was used for both 5 µm and 3 µm quartz grain size with 23 mass% demi water. The standard sintering profile, as described in appendix IV.a, was used to sinter the mould and remove the wax cast shape. In total, 3 casts will be made and are used to measure the method's repeatability. The sample produced by De Vaal was made using their investment, 3D printed wax cast shape (printed by a 3D systems projet 3500w at 16 µm layer height) and vacuum/pressure/vibration invest -ment machine. Because of their casting experience they are able to estimate the shrinkage of the part, so this result will be used to see how close the part's dimensions approach the CAD design. All samples will be casted in silver, because this suited the schedule of the casting company the best. A variety of metals is possible and offered by them, which metal will give the most optimal result has to be investigated in further research.

Accuracy

The cast from de Vaal was compared to the CAD model after all points were translated to approach an optimal result. For each point, the distance to the corresponding point in the CAD file was calculated, resulting in the deviation for each point (results are plotted in figure 66). Besides two measurement errors, all deviations fell within the ±25 µm for the X coordinates and ±22 µm for the Y coordinates. This would be accurate enough for most dimensions of the RIC insert, taken the deviation of the injection moulding process itself, ~±20 µm, into account (page 17).

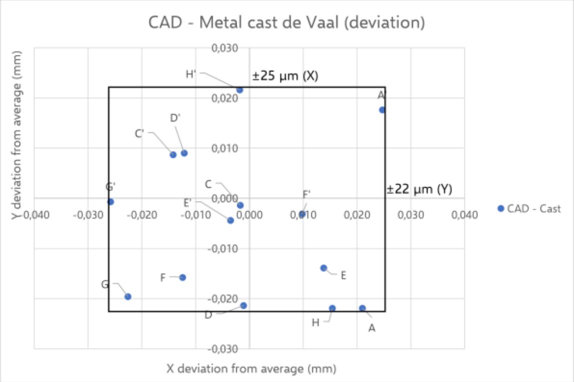


Figure 66: Deviation de Vaal cast

Repeatability

The samples produced along the researched method were not designed to take the shrinkage into account. For that reason, these samples were used to estimate the repeatability of the process; three of the same wax cast shapes were printed and used for casting to measure the deviation between each of the metal parts (figure 67). The deviation between the three parts is plotted in figure 68. The deviation was calculated the same

Figure 67: Casted mould halves with researched investment

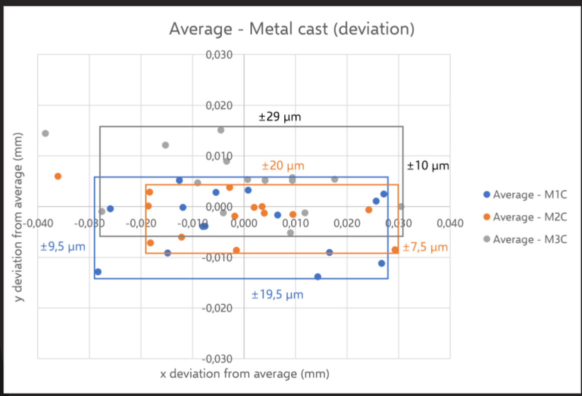


Figure 68: Deviation metal parts made with research investment

way as described in appendix I.b. A small number of peaks higher than ±30 µm likely as a consequence of errors while measuring or imperfections in the cast like air pockets caused by the lack of tools in the investment process. Leaving these peaks outside of the scope, the deviation between coordinates of all 3 points is ±29 µm in X-direction and ±15 µm in Y-direction. The difference between X and Y is remarkably high. Reason for this is unknown, but it is assumed that the shrinkage behaviour of the metal has an influence on the deviation since the metal part is twice as long in X-direction. When the deviations of the parts are reviewed separately, the total deviation is lower. This can be linked to the difference shape of the 3D printed wax cast shaped (appendix IV.d).

Surface roughness

For this method, the surface roughness is an aspect of high importance for the removability of the eventually injection moulded parts and the surface roughness of these parts. Within each phase of this casting process, the surface roughness increases a bit; the print is not perfectly smooth, the investment material is build-up of grains (for both de Vaal as the researched material) and while in the casting step some smoothness is lost too. Between the cast by de Vaal and the cast from the researched investment material a difference in surface roughness can be seen (figure 69 & 70). This is partly due to the 3D printed cast shape, which was made with an old levelling blade (figure 53), leaving small scratches on the surface. Other than that, judging by eye, the researched investment seems to result in a smoother surface. However, further tests have to be conducted and it is also possible that both are sufficient. Difference in accuracy between de Vaal and the research investment is not decisive, although the de Vaal cast seems to be a bit more accurate. For a more reliable result, more samples have to be reviewed.

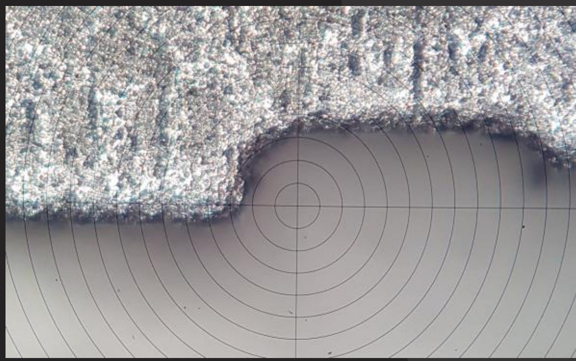


Figure 69: Surface roughness de Vaal cast

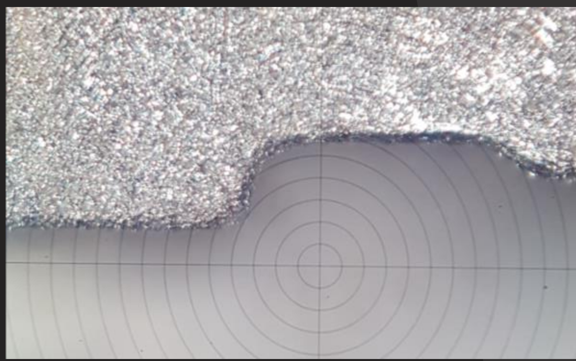


Figure 70: Surface roughness research investment (3 µm quartz)

Conclusion

The micro casting method seems to match all requirements (table 6); tests and development should therefore be continued. Higher deviations in the result analysis might be caused by errors in the measuring process. For a more reliable analysis, it is suggested to use a more advanced way of measuring. Aspects to be tested should be executed in the injection moulding machine and concern the thermal expansion, the hardness, the surface roughness and eventually the geometrical accuracy of the moulded part.

Temperature	✓	Sufficient
Accuracy	✓	±25 µm
Iteration time	✓	1 week
Cost	✓✓	~€200
Tool life	✓	
Form freedom	✓	
Ease of execution	✓	

Table 6: Ceramic milling performance

Ceramic Pressing

Method

This method is an adaptation on the micro casting method and uses the same moulds but in a slightly different configuration. Instead of casting metal into the mould, ceramic is pressed into the cavity. Ceramic pressing was discovered after the initial research phase, during field work for the zirconium milling method.

Hot ceramic pressing principle

The principle of this method is very similar to that of injection moulding. A ceramic ingot is heated till it is viscous enough to be inserted, around 900 °C. As the material is a lithium disilicate glass ceramic, it is able to turn in a viscous form due to the glass that is added to the ceramic (Monmaturapoj et al., 2013) and can therefore be moulded. The material won't be heated until it is in a fully liquid state but till the point it is a thick melt. As mentioned in the research phase, it is still unclear how the ceramic will behave as a mould insert due to its brittleness. To prevent heavy forces being exerted on the insert, it will be flush with master mould unlike plastic mould that stick out 100 µm.

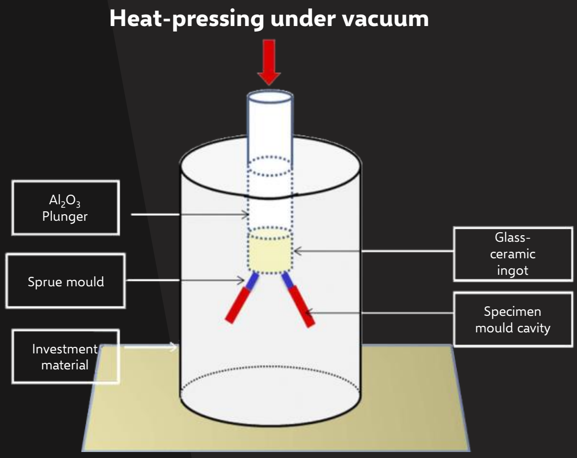


Figure 71: Ceramic hot pressing setup

Procedure

As for micro casting metal, the investment material has to be sintered before it is inserted in the hot pressing machine. Once sintering is completed, the mould should be directly inserted into the hot pressing machine, which will keep it at a temperature of 700 °C. Then, the grass ceramic ingot(s) and a Al_2O_3 plunger are inserted into the mould, in this order. The ingot is heated to a temperature of 900 °C after which a force is applied on the plunger, forcing the glass ceramic melt into the mould.

Figure 72: Glass ceramic ingots

Ceramic press cost and restrictions

The ceramic press is offered by a small amount of brands, but Ivoclar offers the most advanced and reliable ones (). These machines come at a cost of around €10.000 and the ceramic ingots cost ~€100/per 5 ingots of 1.2 cm^3 (where the SLVRIC inserts needs 2 ingots). The build volume is limited by both dimensions and volume; the investment has to be cast in a particular ring with guideline that can be found on the next page and only 2 ingots can be used at the same time limiting the total volume to 2.4 cm^3 including the sprue.

Figure 73: Ivoclar ceramic press furnace

Cast design requirements

Due to the pressure build up inside the cast, there are some rules to follow when investing around the cast shape to ensure the mould won't bread. This method is mainly used in the dental field. Compared to the shapes they cast there, the size of the Sonion injection moulds is on the bigger side of the spectrum but within the methods boundaries. The cavity should be surrounded by a minimum of 10 mm investment, a requirement that is easily met, but can't be higher then 16 mm (figure 74).

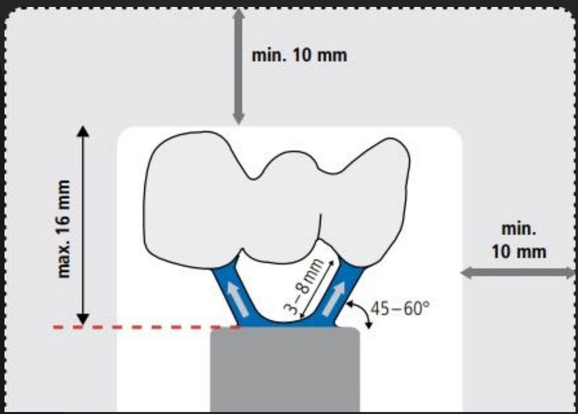


Figure 74: Ceramic press investment configuration

After conferring with the injection moulding team, configuration 2, as seen in figure 75, had been chosen for the first ceramic pressing test. It was thought that the melt would have less flow restrictions over the extruding parts of the cavity.

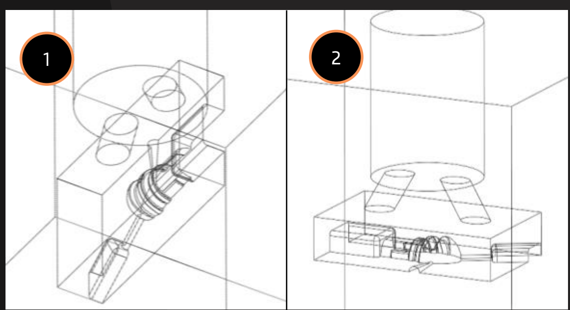


Figure 75: Investment configuration 1 & 2 RIC insert

Most concerns were for the bridge formed between the two injection canals since most of the pressure is on the top surface of this bridge. Because the canals were formed according to the casting guide, it was deemed reasonable to test it first preparatory to increasing the volume of this bridge.

Test result

Apart from the cast configuration, the investment process was initially the same as for micro casting, although the investment material, a combination of gypsum and silica, is optimised for metal casting.

After the first pressing test, it became clear the moulds were not able to withstand the pressure. Cracks formed on the edges the cavity and filled up with the ceramic melt (figure 76). It is assumed that

Figure 76: First ceramic press test

these cracks caused a pressure loss resulting in a part that did not copy the details of the mould as well as possible.

Because the acquired result does not represent the possibilities of this method, it was decided to use the intended investment for the mould making. It is uncertain if this investment material will capture the details of the cast shape as well as the research investment used for the micro casting methods.

One of the 3D printed cast shapes was used by dental technician to create a mould with ceramic pressing investment. After the ceramic was pressed, the investment was not fully removed as it usually is by an aluminium oxide sand blaster as to not lose any accuracy. Instead, the ceramic part was cleaned in an ultrasonic water bath. After the removal, plaster was stuck on the surface of the ceramic cast. The result has sharp edges, but details like print layers are not captured in the ceramic. Furthermore, in the dome region of the mould, the surface looks like a bubble pattern (figure 77). It is unclear what

Figure 77: Ceramic part made with pressing investment

caused this bubble structure to form, but it is known that this will also be captured by the injection moulded parts. In figure 78, a 1.6x magnification of

Figure 78: Bubble pattern ceramic mould surface

the spherical part of the mould can be seen. The remarkable thing is that only at this location the bubbles have been formed, flat surfaces are rough, but do not have this pattern on them.

Accuracy

The deviation between the pressed part and the CAD dimensions was over the limit for the X direction. The average deviation for all points (visualised in figure 79) was 36 µm and the tolerance was ±60 µm (appendix V).

Conclusion

Since ceramic pressing is so closely related to the metal micro casting method, it is fair to compare them in this conclusion. Based on the ability to replicate the cast shape, micro casting is a more suitable solution for the mould production. In the surface of the metal mould, the print layers are clearly visible. The absence of any print layers in the ceramic suggest that the cast shape is not replicated as detailed. However, some details on the ceramic, like the thin wall of the insert cavity and outer edges, were sharper than the metal cast. It is assumed that this is due to the higher back pressure in the ceramic pressing process. Ultimately, the ability to replicate a geometry of micro metal casting is favoured over that of ceramic pressing.
For both methods, the material properties and behaviour in the process can only be estimated since it has not been tested. For both methods, it is likely that after production some post processing is required (flat grinding or other small adjustments). It is likely that this can be done more accurately with a metal product and moreover, the proto engineers are more experienced processing metal.
At last, the usability of the brittle ceramic is questioned in a high pressure environment like the injection moulding machine. Also in this aspect, a metal mould insert is favoured.
To conclude, the metal micro casting method is favoured over the ceramic pressing method. Ceramic pressing is therefore discarded at least till after the full domain of micro metal casting has been explored. The overall performance of the ceramic pressing method can be seen in table 7.
Because the cause of the high surface roughness is unclear, it could be either the investment or the ceramic material, there might be room for optimisation. It could be attempted to optimise the strength of the micro casting investment by increasing the quartz particle concentration to uncover the reason for the high surface roughness. Furthermore, the ceramic pressing investment used could be investigated.

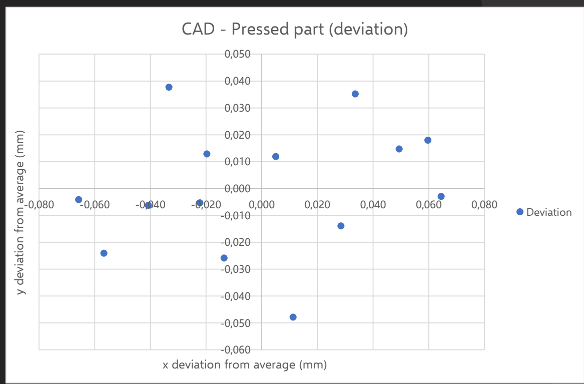


Figure 79: Deviation from corrected CAD dimensions (taken shrinkage into account) for the pressed ceramic part

Temperature	✔	Sufficient
Accuracy	✘	Insufficient
Iteration time	✔	3 days
Cost	✔✔	~€200
Tool life	?	
Form freedom	✔	
Ease of execution	✔	

Table 7: Ceramic milling performance

Powder Injection Moulding

Method

For the production of prototyping parts is the main problem that the 3D printed mould inserts are barely able to withstand the heat released by the melt that has a temperature of approximately 300 °C. Injection moulding metal therefore seems illogical. However, this method uses a binder filler system that allows the material to be injected at a temperature of around 180°C. A full explanation of the method can be found on page 27.

The mould

A mould of a region of a mould half was created and printed (figure 80). Making a mould of the entire mould half was not possible due to the dimensions of the mother mould cavity (figure 81). In case this method is most suitable for the productions of the mould, a new mother mould must designed and produced. Since the IM team is already looking into the possibilities of new moulds, this should not be a problem.

Test plan

Originally, testing was split up into two phases, namely the production of the green body by injecting the feedstock into the printed mould, and the sintering of the green body. Sintering can't be done at Sonion because of the absence of the right oven, tests can only be partly conducted at a different company. Furthermore, acquisition of a feedstock that has the appropriate metal grain size was an important step in the process and ideally should be from a company that can also sinter the parts and has experience into how to do this in a most optimal way.

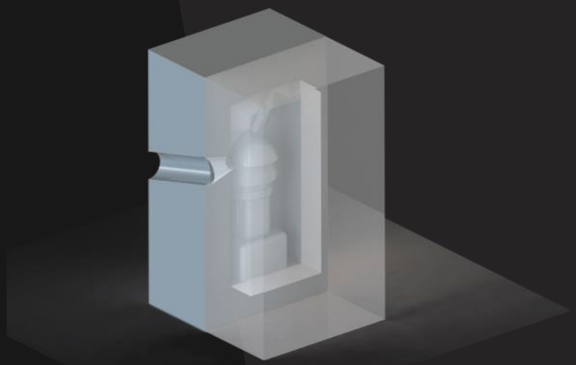


Figure 80: Mould of the intended mould

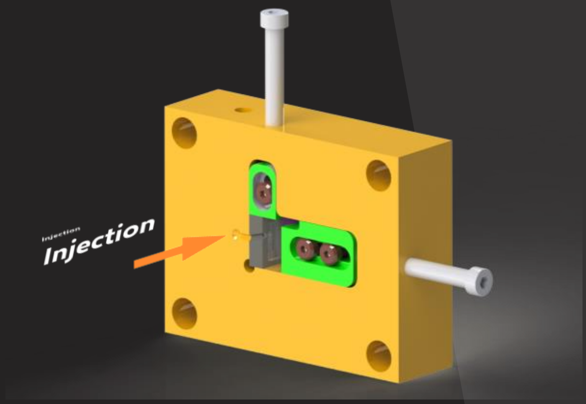


Figure 81: Mould placed inside mother mould

Collaboration

In order to acquire the right feedstock and to sinter the moulded parts, a collaboration with Demcon was set up. Demcon is interested in the production of low volume because new customers request a couple of hundred samples before ordering. They don't have a mould for these purposes and are therefore willing to join forces.
One of their engineers would come over to test injection moulding with their powder feedstock into the 3D printed moulds produced by Sonion. After a range of samples would have been produced, the samples were to be sintered at Demcon and analysed at Sonion and Demcon.
However, due to the full schedule of Demcon at that time, no appointment could be scheduled. They remain open to do business with Sonion for the future and are still interested in this way of mould production.

High volume shots

The main uncertainty for this method is the temperature resistance of the mould. Even though the binder metal system is injected at a temperature of 190 °C, relatively low compared to materials used now like PA66 at 290 °C, the shot volume is much higher than the injected parts that have been tested with. A higher volume results in a higher thermal capacity, which might cause the mould to heat up more than when it is injected at a higher temperature with a lower shot volume. In order to test this without the required feedstock, a material, Polyoxymethylene (POM), with an equal injection melt temperature was used to test the mould.

Injection moulding results
For the moulding test, two 3D printed moulds (material) were used. As for all moulding procedures, the first mould was used to calibrate the injection moulding machine. At first, some difficulty filling the mould was experienced. Once the mould was filled, mainly by increasing the injection velocity, the back pressure could be set. In figure 82, the first 5 pictures are made with the first mould and the second 4 of the second mould.

The effect of the higher heat capacity caused by the shot volume was immediately visible when opening the mould. This was done after a cooling down time equal to that of the reference parts, which is too short of a period for a volume this size. As can be seen in the left top sample in figure 82, the plastic had not fully solidified causing deformation when opening the mould.

For a first test of filling high volume moulds, the results were positive. Details in the result, like layers and edges, can be seen to be substantially sharper than in any other method. Due to time restrictions, no parts for a geometrical analysis could be made, but it is assumed that parts can be produced with tolerances of ±20 μm and an average deviation of 9 μm, based on previous research (page 16). The surfaces appear not to be fully planar, but as with the micro casting mould, all sides could be extruded and flatted after or before sintering in case optimisation of the moulding process does not result in the expected Improvement, i.e. planar surfaces. Moulds are able to withstand up to 5 shots, where only 1 successful shot is needed.

Temperature	✓	Sufficient
Accuracy	?	±20 μm
Iteration time	✓	1-2 days
Cost	✓	~€800
Tool life	?	
Form freedom	✓	
Ease of execution	?	

Table 8: Powder Injection Moulding performance

Conclusion
Up to the injection moulding step, this method seems to be a promising technique to acquire metal moulds. Though, more testing needs to be conducted regarding the moulding of the metal powder feedstock and the sintering step. The former was tested with a similar material, with positive result, and the latter should not result in too many difficulties, according to Demcon, due to the beneficial flat configuration of the shape. Usually, only thicker shapes or shapes with overhang form real difficulty. Overall performance of the method can be seen in table 8X.

Figure 82: Powder Injection Moulding test pieces; each row from one mould, moulded from left to right

Synthesis

Method overview
Plan of action

In the synthesis section, the results acquired in the validation phase are used to provide a well-founded plan of action for the integration of this research.

Of each method, the major findings will be discussed and combined into visuals to indicate its strengths and weaknesses. The performance on the three primary criteria will be covered and the decision matrix will be discussed.

The overview is used to make a clear plan of action. The physical performance is compared to the feasibility of each method, guiding the decision making. Then, a recommendation is written for the continuation of the results of this research.

Method overview

Before a reliable recommendation can be done, the results of the validation phase have to be compared. Their performances on the three main pillars of this research (figure 83), cost, accuracy and time, are the primary factors for decision, but also the minor criteria will be taken into account. On page 50, a visual of the final decision matrix can be found, summarising all performances.

Metal 3D printing

When looking at the performances of the metal 3D printing industry, it doesn't decrease the price by a substantial amount and neither does it decrease the time as much as desired. As discussed on page 31, metal can be printed with very high accuracy within a volume that is (too) small or it can be printed not accurately enough for a bigger volume. The high accuracy electrochemical fabrication is the most accurate alternative way to produce the mould out of all methods. A combination between the thermal based and the electrochemical based printing would hypothetically form an ideal solution.

Ceramic printing

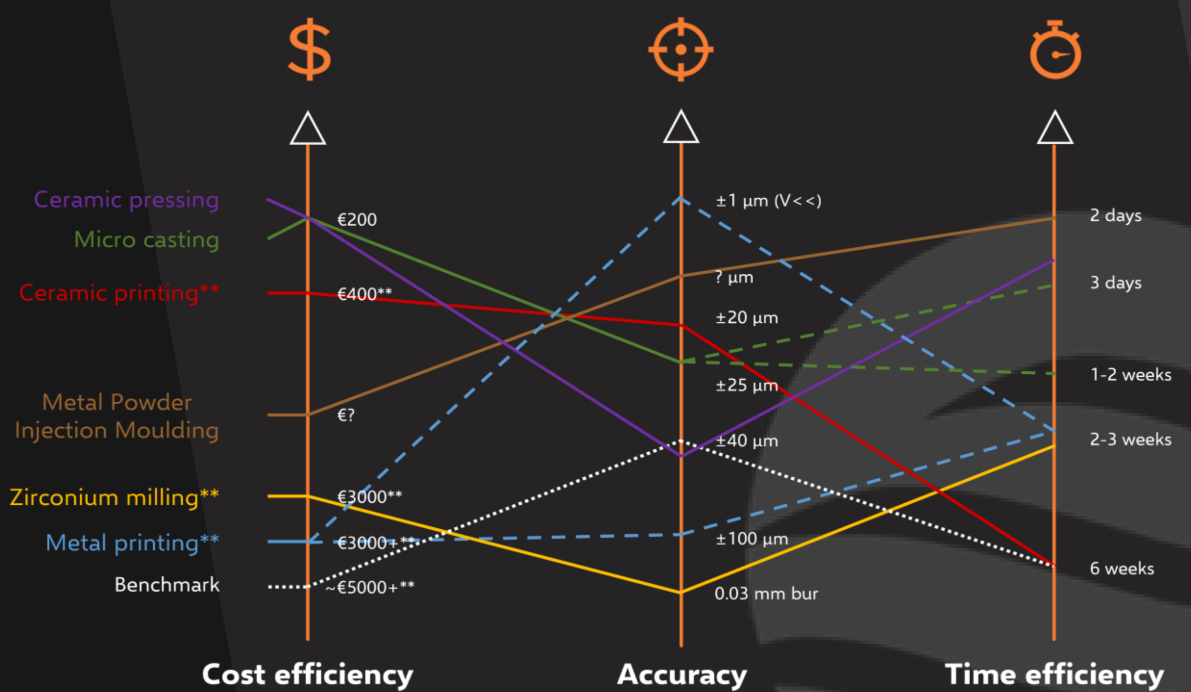
This method performs very well on both accuracy as cost, but this is only possible by a long iteration time. The time would remain 6 weeks, as it is when the mould is produced the traditional way. Taking into account that this iteration time is for the Lithoz' process, Admatec might produce parts quicker, but it is likely that this will have a negative impact on the accuracy resulting in tolerance higher than the ±20 µm reached by Lithoz. Due to the iteration time of the Lithoz process and the entangled interests in Admatec, it was decided to stop investigations into this method.

Zirconium (CNC) milling

Milling of zirconium with one of the most accurate ceramic powder CNC machines, the Zirkonzahn, does not perform as well as needed for any of the three main criteria. The method turned out to be more expensive than estimate, partly due to the experimental nature of the method causing it to be too time consuming and unable to reach the right accuracy due to the size of the bur.

Micro casting

The all steps in the micro casting process have been researched in detail. The tolerances for the production of the mould are within the requirements of this project. When the method is fully outsourced, the production of on mould half



*Cost estimations are made based on one halve of a RIC insert mould | **Outsource

Figure 83: Method performance on primary criteria

	Micro Casting	Ceramic Pressing	Powder Injection Moulding	Ceramic 3D printing	Zirconium milling	Direct Metal Printing
Temperature	✓	✓	✓	✓	✓	✓
Accuracy	✓	✗	?	✓	✗	✗
Iteration time	~	✓	~	✗	✓	~
Cost	✓	✓	✓	✓	~	~
Tool life	✓	?	✓	?	?	✓
Form freedom	✓	✓	✓	✓	~	✓
Ease of execution	✓	✓	?	✓	✓	✓
Surface roughness	?	✗	?	?	?	?

Figure 84: Filled in decision matrix

is €175. In house production of the mould and only outsourcing the casting procedure will result in an increase in price, but doesn't come with an immediate increase in accuracy or a shorter iteration time. A shorter iteration time can be realised this way since a casting company only has to cast the shape. Higher accuracy could be achieved by optimising both the 3D printed wax shape and the investment material and procedure.

Ceramic pressing

In many ways, ceramic pressing works the same as micro casting and therefore has similar results as that method. Though, because the investment used in the micro casting method is optimised for metal casting, it is not strong enough to withstand the forces the mould is exposed to in ceramic pressing. Consequently, ceramic pressing specific investment has to be used for this method. The usage of this method could be the cause of the accuracy difference between micro casting and ceramic pressing. Because the ceramic moulds have never been tested in the injection moulding machine, it is unclear if the brittleness of the mould will be a problem during the injection process, hence the question mark for tool life. Instead of the mould protruding the mother mould surface (by 10 to 20 μm), which is usual for 3D printed moulds, the mould will be flush with the surface. This way, the clamping force exerted on the mould insert is minimised. Micro casting outperforms ceramic pressing by a substantial amount, mainly on accuracy, surface roughness and post processing possibilities. There might be room for improvement, since it is unclear what causes the high surface roughness.

Powder Injection Moulding

As a consequence of a time shortage and misaligning schedules, the method could not be researched as extensive as other methods. Potentially, Powder Injection Moulding is the most accurate method to produce metal moulds. Within this research, injection moulding was found to be the most accurate technique to replicate a 3D printed part. The 3D printed moulds seem the withstand the thermal heat capacity of the shot, but more research is required to see if it can handle the even higher heat capacity of the micro powder feedstock, compared to POM used during the tests. Furthermore, it is not clear how a mould insert of this size behaves in the sintering phase.

Decision matrix

The final decision matrix, of which a simplification can be seen in figure 84, can be found in appendix VI.a and contains additional information concerning the methods. The iteration time and cost of each method have been estimated for each part, but also initial investments have been accounted for (appendix VI.b).

Conclusion

Plan of action

The goal of this project is to identify methods that decrease cost and production time but maintain a similar accuracy as the benchmark (page 25). After summarising the validation results, a decision has to be formed on which of the selected methods does this best. A graphic overview of this can be seen in figure 85. Additionally, a plan of action is proposed on how the development could be continued.

Method selection

Forming a well-founded conclusion was done with the use of the final decision matrix, the impression given by the method and discussions with colleagues. The outcome is visualised in the form of a graph that has feasibility and performance on respectively the X and Y axis. The feasibility is comprised of the criteria iteration time, cost, form freedom and ease of execution. Among the performance are accuracy, tool life and surface roughness. Purposefully, the temperature resistance criteria is left out, because all methods are expected to perform more than sufficient. All methods are plotted as rectangular boxes, covering a region on both X and Y axis. Methods could not be plotted as points or lines, because for all method there are still uncertainties and there is room for optimisation.

Method to discard

Zirconium milling can be discarded because of the high price, the high iteration time and because small shapes can't be produced due to the size of the milling bur. This results in a bad score for both the feasibility and the performance.

Ceramic pressing is outperformed by metal casting. Since a ceramic material does not have a real benefit over metal in this application, the method can be discarded.

Methods to keep an eye on

In this category, the chances of increased performance for a method are likely. The method should therefore be kept in mind throughout the following years and could serve as an improvement on the method that is being used for the mould production.

If the build volume of Direct Metal Printing, more specifically the electrochemical form, would be

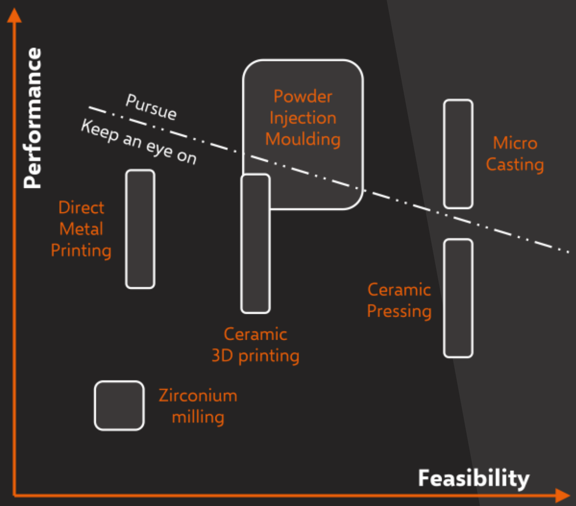


Figure 85: Recommendation plot

higher, the method is expected to perform very well on the performance scale. A work around the low volume is dividing the design in sub parts and joining these afterwards, which lowers the performance and the feasibility consequently because of a price and time increase and an accuracy decrease.

The main downside of Ceramic 3D printing is the high iteration time of 6 weeks as a consequence of the optimisation of the tolerance (±20 μm) for certain dimensions. On the feasibility scale, this method scores too low to be considered to pursue. Yet, this verdict is based on the process of one of the two qualifying ceramic 3D printers. Throughout the following years, this method could be improved resulting in a decrease in sintering time making the method more feasible.

Methods to pursue

Micro casting is the method that is proven to meet all requirements and advantageous due to its ease of integration. The only uncertainty is the surface roughness of the mould, that can only be tested in the injection process and could also be improved in various ways.

Metal Powder Injection moulding is a very promising yet still uncertain method. Circumstances (page XX) made it difficult to test the capabilities of this method to an extend that is required to form a good judgement. A test with material similar to the metal powder feedstock resulted in a very detailed replication of the 3D printed mould. No reliable geometrical analysis could be conducted, but it is assumed that tolerances of <±20 µm and an average deviation of 9 µm can be achieved based on previous research (page XX). The likelihood of this is increased by the fact that a 3D printed mould only has to withstand one shot since the machine can be setup with additionally printed moulds. However, a big uncertainty is the influence of the sintering phase on the geometry, but it is expected by experts from Demcon that no strange behaviour will occur. For these reasons, continuation of the method is recommended although many variables are still unknown.

Continuation – Micro Casting

For the continuation of testing the micro casting method, it is not recommended to start testing in-house. For full in-house production, an investment mixer, an oven and a vacuum/pressure metal casting machine are required and need to be purchased. Outsourcing the production to a metal casting company like de Vaal and continuing the collaboration is advised for initial testing, moreover because their casting result was very close to the results of the research investment. Once accuracy or surface roughness improvements are needed, it is advised to acquire an investment mixer and continue the micro casting research (appendix XX). Beneficial is the flexibility of de Vaal; the customer can choose which part of the process is facilitated by them.

As a start, the mould halves acquired during this research could be tested in the injection moulding machine with a 3D printed counterpart. This way, the difference between the 3D print and the metal cast becomes visible immediately if differences occur. The mould half provided by de Vaal is best suited for this test, since the dimensions are very close to the CAD model. However, a slight modification is needed in one of the insert cavities due to an air bubble.

In case the surfaces are not as flat as required, it is suggested to extrude these surfaces by a small amount and flatten these with a surface grinder.

Inserts could either be 3D printed or casted. Because no substantial wear has been seen during the injection moulding runs, the first tests can be executed with 3D printed inserts.
When results of the tests with the injection moulding machine are positive and the method is proven to be fully functional, the production of the moulds can be done in house to decrease the iteration time. However, this will very likely come with a cost increase.

Continuation – Powder injection moulding

Although some aspects of this method are still unclear, it is highly recommended to continue the collaboration with Demcon to reveal the possibilities of this method. It is likely that the 3D printed moulds are capable of resisting the heat for more than one shot, while only one shot is required. The machine can be configured with similar 3D printed mould inserts, so a fresh mould insert can be used for the production of the final mould.

Continuation of this method is recommended because of the highly accurate properties of injection moulding and the possibly to produce steel moulds. The moulding step is followed by a sintering step, converting the so-called green body into a 99% dense metal part. This is done by heating the part by a profile with a peak at 1400 °C, a process mastered by the engineers at Demcon. Therefore, a collaboration is suggested in which Sonion and Demcon explore the possibilities of producing injection moulding moulds by injection moulding. For an optimal result, another test with POM is suggested to see if a better result can be reached by changing the gate size or optimising the back pressure. Also this step could be done with the experience of Demcon engineers before testing their feedstock.

Overall integration

Because the complexity and features differ substantially for each part, it is suggested that for every part a part specific approach is determined. Often, in the early stages of the production, 3D printed moulds should be tried to optimise the mould design and to uncover process limitations. When the design is verified, a switch should be made to the production of a metal casted mould for its assumed capabilities of producing a bigger batch at a more constant and higher accuracy. If the metal mould has to be modified to achieve a higher accuracy, a range of different methods can be tested like etching, uniform sanding but also post casting milling. By blowing the CAD design up uniformly, the excess skin can be milled down by a CNC machine to possibly increase the accuracy and decrease the surface roughness. The possibility to work with metal mould will enable Sonion to have a more accurate, reliable and constant injection moulding process.

Reflection

After completing this thesis, it is appropriate to reflect on the course of actions over the span of this project. Planning, managing tasks and technical aspects will be covered.

Since a big part of this research concerned techniques that were not available within Sonion, a lot of business took place outside of the company. In general, this went well because it was considered that this would cost extra time and therefore this process was started early. Looking back, metal casting could have been pushed forward a bit. In depth validation of the investing process was well founded, but simultaneously the actual metal casting could have been set in motion earlier by focussing on fully outsourcing the production. In-house production took longer than expected due to required time for the 3D printed wax cast shape to be produced. Ordering a metal cast sooner would have changed the perspective on the micro casting method in an earlier stage.

Geometrical analysis could have been done with more advanced tools resulting in more accurate results. Due to time restrictions, it was chosen to revert to the Mitutoye Smartscope since it was more accessible. Usage of the InfiniteFocus by Alicona was not possible all the time due to a change in machines.

Communication within the supervisory team went well, only positive remarks have been heard. The weekly updates helped the team to be aware of the direction and the status of the project while it was a tool for me to keep track of the progress and choose a direction accordingly. In the future, weekly updates will remain part of the process, if not for communication purposes only as a tool to make well founded decisions.

A valuable lesson learned in the last 20 weeks, is that collaborations with experts give so much more insights than doing everything by yourself. Discussing your project gives a fresh input from a different perspective, namely one that knowledgeable in their profession. This way, new ideas, or adaptations of different ideas, come to the table.

While doing this project, I got the feedback that I was working very independently, in the positive sense of the word, and that I took good initiatives. Previously, I was not so aware that these were part of my features. Due to the positive remarks, I plan to continue this work ethic.

During the last 20 weeks, it came to my attention that I could be more proactive in sharing my results with colleagues. This might also be a bit of the downside of working independently since you are a bit more under the radar. What also did not help, was the fact that my project was outside the scope of what other were working on on a day to day basis.

Overall, I'm content with the outcome of this project. In my opinion, relevant, suitable and promising new methods have been identified to produce moulds for the injection moulding machine, which was the job I was asked to carry out. During this project, I became more aware of what it means to work in the industry, and I would like to continue my personal development in this direction.

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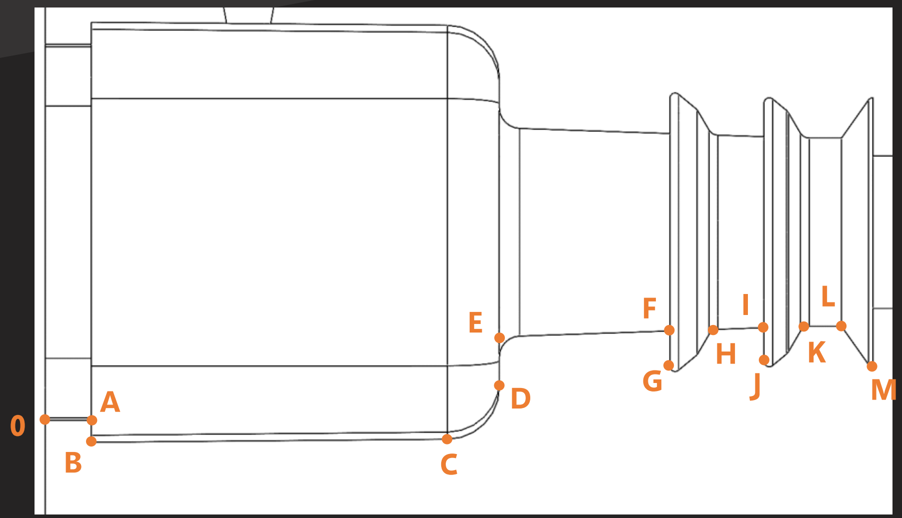
Appendix

Appendix I.a

Decision matrix selected methods



	0		A		B		C		D		E		F		G		H		I		J		K		L		M		
State	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	
#6	0,0000	0,0000	0,3683	0,0000	0,3723	-0,2031	3,7514	-0,1608	4,2408	0,3491	4,2607	0,8396	5,8123	0,8847	5,8101	0,6355	6,2617	0,9165	6,7027	0,9299	6,7051	0,7059	7,1355	0,9567	7,4647	0,9606	7,8139	0,6835	
#6'	0,0000	0,0000	0,3282	-0,0077	0,3280	-0,2109	3,7072	-0,2393	4,2072	0,2602	4,2373	0,7502	5,7896	0,7628	5,7821	0,5137	6,2395	0,7852	6,6807	0,7893	6,6784	0,5653	7,1140	0,8071	7,4432	0,8041	7,7865	0,5197	
#8	0,0000	0,0000	0,3352	0,0000	0,3332	-0,2144	3,6950	-0,2311	4,1835	0,2741	4,1947	0,7344	5,7481	0,7764	5,7453	0,5110	6,1955	0,7938	6,6386	0,7923	6,6329	0,5583	7,0550	0,8150	7,3809	0,8151	7,7357	0,5065	
#8'	0,0000	0,0000	0,3752	0,0000	0,3732	-0,2144	3,7350	-0,2311	4,2235	0,2741	4,2347	0,7344	5,7881	0,7764	5,7821	0,5110	6,2355	0,7938	6,6786	0,7923	6,6729	0,5583	7,0950	0,8150	7,4209	0,8151	7,7757	0,5065	
#9	0,0000	0,0000	0,3659	0,0000	0,3648	-0,1971	3,7106	-0,1514	4,2213	0,3659	4,2382	0,8456	5,7618	0,8966	5,7616	0,6292	6,1938	0,9068	6,6546	0,9266	6,6617	0,6748	7,0895	0,9577	7,4187	0,9601	7,7609	0,6600	
#9'	0,0000	0,0000	0,3658	-0,0077	0,3606	-0,2047	3,7066	-0,2291	4,2280	0,2774	4,2550	0,7567	5,7793	0,7757	5,7735	0,5084	6,2114	0,7769	6,6725	0,7870	6,6744	0,5351	7,1080	0,8090	7,4372	0,8045	7,7730	0,4973	
#12	0,0000	0,0000	0,3722	0,0091	0,3785	-0,2258	3,6559	-0,2253	4,2255	0,3131	4,2446	0,7592	5,8234	0,7823	5,8232	0,5100	6,2567	0,7894	6,7119	0,8170	6,7152	0,5592	7,1301	0,8032	7,4892	0,8172	7,8131	0,5149	
Average	0,0000	0,0000	0,3604	-0,0016	0,3601	-0,2139	3,7012	-0,2312	4,2211	0,2812	4,2429	0,7501	5,7951	0,7743	5,7902	0,5108	6,2358	0,7863	6,6859	0,7964	6,6852	0,5545	7,1118	0,8086	7,4476	0,8102	7,7871	0,5096	
CAD	0,0000	0,0000	0,4400	0,0000	0,4400	-0,2100	3,8700	-0,1800	4,3600	0,3800	4,3600	0,8200	6,0000	0,8700	6,0000	0,5300	6,4100	0,8700	6,9100	0,9000	6,9100	0,5700	7,2900	0,9000	7,6500	0,9100	7,9500	0,5200	
CAD'	0,0000	0,0000	0,3612	-0,0053	0,3587	-0,2111	3,7202	-0,2227	4,2070	0,3202	4,2123	0,7513	5,8200	0,7807	5,8159	0,4475	6,2217	0,7758	6,7121	0,7992	6,7081	0,4758	7,0844	0,7947	7,4373	0,8001	7,7266	0,4144	
#9 vali			0,3256	0,0000	0,3276	-0,2142	3,6267	-0,2234	4,1683	0,3058	4,1789	0,7552	5,7385	0,7835	5,7389	0,5357	6,1693	0,7975	6,6293	0,8056	6,6277	0,5788	7,0401	0,8247	7,3760	0,8238	7,7301	0,5304	
Coordinate diff																													Average
Average - #6'			0,032	0,006	0,032	-0,003	-0,006	0,008	0,014	0,021	0,006	0,000	0,006	0,012	0,008	-0,003	-0,004	0,001	0,005	0,007	0,007	-0,011	-0,002	0,002	0,004	0,006	0,001	-0,010	0,008
Average - #8'			-0,015	-0,002	-0,013	0,000	-0,034	0,000	-0,002	0,007	0,008	0,016	0,007	-0,002	0,008	0,000	0,000	-0,007	0,007	0,004	0,012	-0,004	0,017	-0,006	0,027	-0,005	0,011	0,003	0,008
Average - #9'			-0,005	0,006	-0,001	-0,009	-0,005	-0,002	-0,007	0,004	-0,012	-0,007	0,016	-0,001	0,017	0,002	0,024	0,009	0,013	0,009	0,011	0,019	0,004	0,000	0,010	0,006	0,014	0,012	0,009
Average - #12			-0,012	-0,011	-0,018	0,012	0,045	-0,006	-0,004	-0,032	-0,002	-0,009	-0,028	-0,008	-0,033	0,001	-0,021	-0,003	-0,026	-0,021	-0,030	-0,005	-0,018	0,005	-0,042	-0,007	-0,026	-0,005	0,017
																													0,011
CAD - #6'			0,033	0,002	0,031	0,000	0,013	0,017	0,000	0,060	-0,025	0,001	0,030	0,018	0,034	-0,066	-0,018	-0,009	0,031	0,010	0,030	-0,089	-0,030	-0,012	-0,006	-0,004	-0,060	-0,105	0,028
CAD -#8			-0,014	-0,005	-0,015	0,003	-0,015	0,008	-0,016	0,046	-0,022	0,017	0,032	0,004	0,034	-0,063	-0,014	-0,018	0,033	0,007	0,035	-0,082	-0,011	-0,020	0,016	-0,015	-0,049	-0,092	0,027
CAD -#9'			-0,005	0,002	-0,002	-0,006	0,014	0,006	-0,021	0,043	-0,043	-0,005	0,041	0,005	0,042	-0,061	0,010	-0,001	0,040	0,012	0,034	-0,059	-0,024	-0,014	0,000	-0,004	-0,046	-0,083	0,024
CAD - #12			-0,011	-0,014	-0,020	0,015	0,064	0,003	-0,018	0,007	-0,032	-0,008	-0,003	-0,002	-0,007	-0,062	-0,035	-0,014	0,000	-0,018	-0,007	-0,083	-0,046	-0,009	-0,052	-0,017	-0,086	-0,101	0,028
																													0,027

Appendix III build up

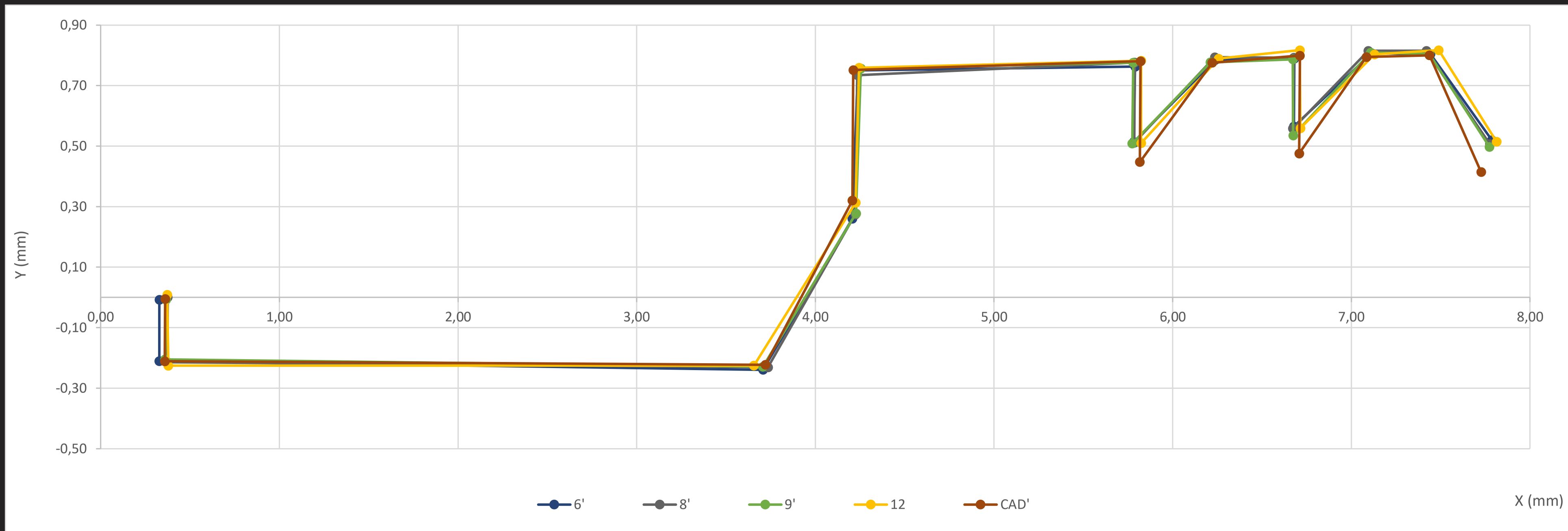
Appendix III has 3 parts. In III.a, reference points and the raw data + calculated results can be seen, in III.b this data is plotted in a graph. In appendix III, a summary of the moulding procedure, data analysis and results is shown to communicate the current status of the injection moulding process to other department heads, as requested by the IM team.

Appendix III.a

In the figure, the measured points can be seen. In the table, the raw coordinates and the translated coordinates (#X') can be seen. When a row is marked grey, the adjusted coordinates (#X') are used for the calculations.

Appendix I.b

Plot of adjusted (6’, 8’, 9’), measured (12) and adjusted CAD’ coordinates.



Appendix I.b

Slides repeatability method made for IM team

Repeatability of injection moulding with 3D printed moulds

Mathijs de Heer

Part:	LM-RIC E50D Housing Front
Used material:	PA-66 (@290 °C)
Final material:	Ultramid® A3EG6 (@300 °C)

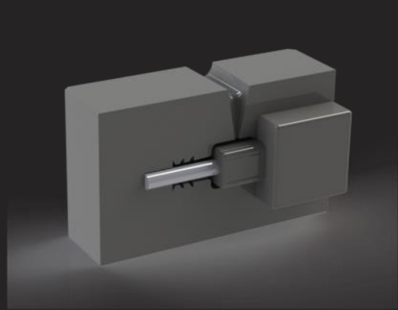


Figure 1: Mould design

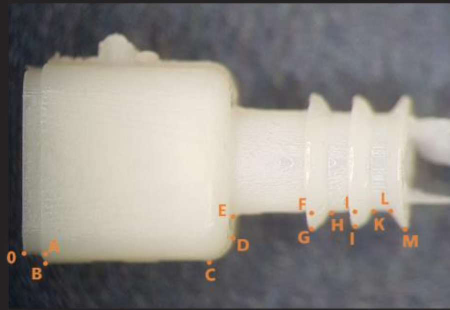


Figure 2: Moulded RIC housing + reference points

Figure 3: Collection of moulded parts from two moulds

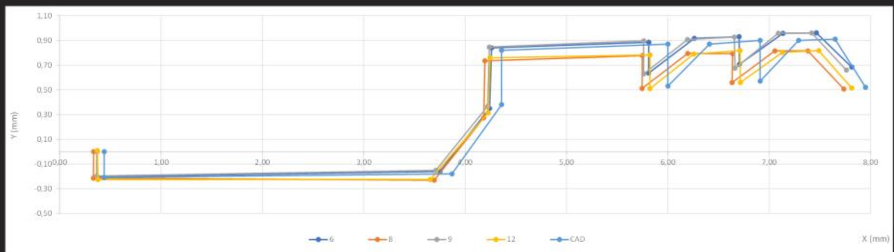


Figure 4: Initial result geometrical analysis

- ~15 shots per mould before failure.
- From the same mould, sample 6, 8, 9 and 12 were chosen for geometrical analysis and were picked for their completeness (figure 3).
- Using the Mitutoye SmartScope, X and Y coordinates of the reference point (figure 2) have been measured for each sample and were plotted (figure 4) together with the original CAD coordinates.

Method

- Due to misalignment in the Alicona, the coordinates for each sample have been rotated using the rotation matrix and have been translated for a reliable comparison.
- CAD coordinates have been rotated (to align with measurements) and scaled (to counteract the shrinkage of the part)

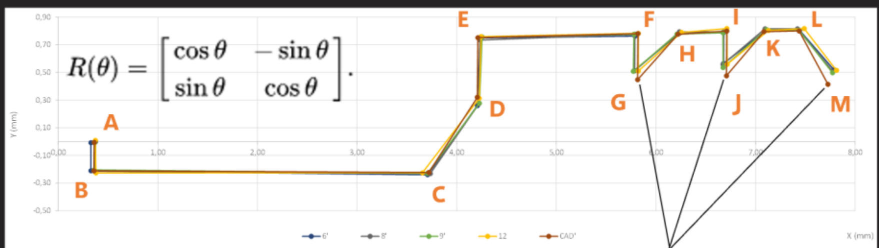


Figure 4: Adjusted coordinates

Snap fit not fully filled (next page)

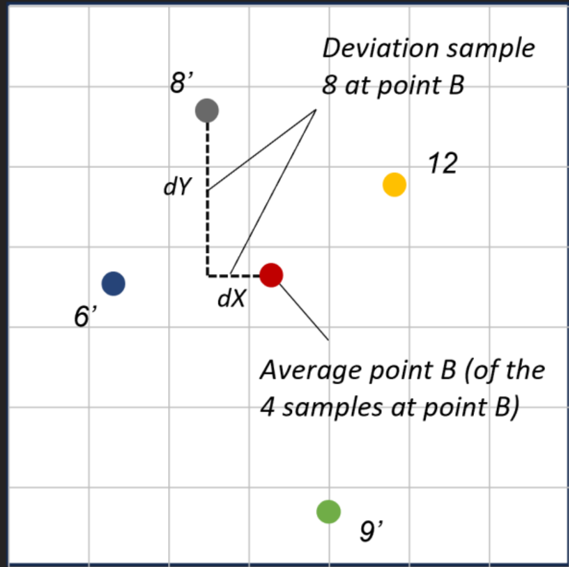


Figure 4: Deviation approach at point B

- To calculate the deviation, the average of all samples is calculated for each point. The deviation of each sample at that point is the distance to this average (figure 6), which is split up in a dX and dY part to gain possibly more insights.

Result

- Average deviation: ±11 µm. More important are the peaks, highlighted in orange, with a high of 42 µm (table 1).
- Measuring errors are likely for points C&D due to the big fillet.
- Average deviation from CAD mainly influenced by sharp snap fits (points G, J and M) that were not filled completely (figure 4&5) resulting in higher average.
- Figure 5 shows an indent at the feet of the snap fit, which is bigger for the later shots. In figure 6, a worn out gate and sprue, after 15 shots, can be seen.

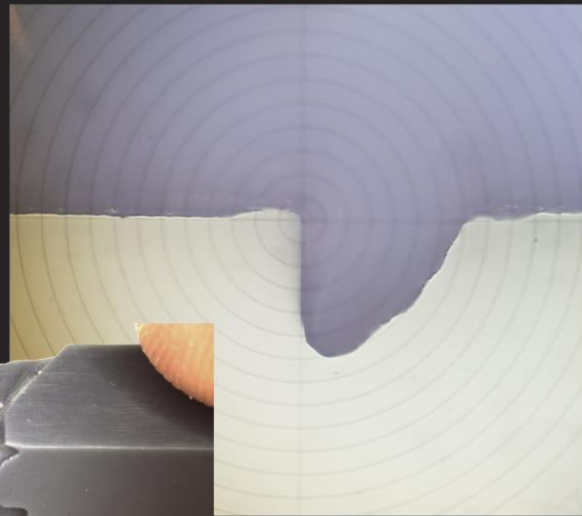


Figure 5: Snapfit too round at the edge and an indent caused by wear at the cross-hair

Figure 6: Worn out sprue after 15 shots

		0		A		B		C		D		E		F	
		X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
	Coordinate diff														
Deviation	Average - #6'			0,032	0,006	0,032	-0,003	-0,006	0,008	0,014	0,021	0,006	[illegible]	0,006	[illegible]
	Average - #8'			-0,015	-0,002	-0,013	0,000	-0,034	0,000	-0,002	0,007	0,008	0,016	0,007	-0,002
	Average - #9'			-0,005	0,006	-0,001	-0,009	-0,005	-0,002	-0,007	0,004	-0,012	-0,007	0,016	-0,001
	Average - #12			-0,012	-0,011	-0,018	0,012	0,045	-0,006	-0,004	-0,032	-0,002	-0,009	-0,028	-0,008
CAD deviation	CAD - #6'			0,033	0,002	0,031	0,000	0,013	0,017	0,000	0,060	-0,025	0,001	0,030	0,018
	CAD -#8			-0,014	-0,005	-0,015	0,003	-0,015	0,008	-0,016	0,046	-0,022	0,017	0,032	0,004
	CAD -#9'			-0,005	0,002	-0,002	-0,006	0,014	0,006	-0,021	0,043	-0,043	-0,005	0,041	0,005
	CAD - #12			-0,011	-0,014	-0,020	0,015	0,064	0,003	-0,018	0,007	-0,032	-0,008	-0,003	-0,002

		G		H		I		J		K		L		M		
		X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	
	Coordinate diff															Average
Deviation	Average - #6'	[illegible]	-0,003	-0,004	0,001	0,005	0,007	0,007	-0,011	-0,002	0,002	0,004	0,006	0,001	-0,010	0,008
	Average - #8'	0,008	0,000	0,000	-0,007	0,007	0,004	0,012	-0,004	0,017	-0,006	0,027	-0,005	0,011	0,003	0,008
	Average - #9'	0,017	0,002	0,024	0,009	0,013	0,009	0,011	0,019	0,004	0,000	0,010	0,006	0,014	0,012	0,009
	Average - #12	-0,033	0,001	-0,021	-0,003	-0,026	-0,021	-0,030	-0,005	-0,018	0,005	-0,042	-0,007	-0,026	-0,005	0,017
																0,011
CAD deviation	CAD - #6'	0,034	-0,066	-0,018	-0,009	0,031	0,010	0,030	-0,089	-0,030	-0,012	-0,006	-0,004	-0,060	-0,105	0,028
	CAD -#8	0,034	-0,063	-0,014	-0,018	0,033	0,007	0,035	-0,082	-0,011	-0,020	0,016	-0,015	-0,049	-0,092	0,027
	CAD -#9'	0,042	-0,061	0,010	-0,001	0,040	0,012	0,034	-0,059	-0,024	-0,014	0,000	-0,004	-0,046	-0,083	0,024
	CAD - #12	-0,007	-0,062	-0,035	-0,014	0,000	-0,018	-0,007	-0,083	-0,046	-0,009	-0,052	-0,017	-0,086	-0,101	0,028
																0,027

Table 1: Deviation results

Appendix II

Research evaluation matrix

Performances all researched methods

Throughout the research phase, all data of the researched methods was gathered in a matrix. During the research, the focus was on finding limitations that would make continuation of the method impossible. Furthermore, methods (in the left column) are labelled green, yellow, red or grey. Red and grey both meaning the method is discarded, yellow meaning the method could only partly cover all needs and green meaning the method is suitable for further research.

	Method	Pressure	Temperature	Accuracy	Time	Form freedom	Tool life	Cost	Ease of integration	Additional comments	Source
Subtractive	Micro-EDM			High		Medium		High	Easy	Ceramics possible	https://w
	Micro-ECM			High		No cavities(die is pushed in)			Difficult	Metal master die needed	https://w
	Electrical Discharge Machining (Manual)										
	Laser Beam Machining					Only in 2D			Neutral		
	Electron Beam Machining					Only in 2D			Neutral	Thin material	
	Micro (CNC) machining		High	High		High		High	Neutral		
	Photo-chemical-machining					Only in 2D			Neutral		
Additive	Surface coating					Only a thin layer		Low		Could be an addition to another method for surface	
	Direct or digital writing (MJT) (DoD)			Accuracy not high enough; smalles nozzle = 0.1m		High				Wide range of material among which silver and ceramics	https://w
	Micro casting		High	High		High		Relatively low	Neutral	Extensive research, "microcasting.docx", research folder	
	Stereolithography (SLA)		Plastics too low					High		Somos perform, ceramics also interesting	
	Melting (SLM)			Very high		Very high		Very high (metal)	Easy	Metals possible	
	Sintering (SLS) (MLS)										https://w
	Direct Light Processing (DLP)			High		High			Easy		
	Projection MicroStereoLithography (PμSL)		Too low	Very high		High			Easy	No metal, no ceramics	
	Photo-electro-forming									Metal master die needed	https://w
	Material (nanoparticle) jetting		High	High		High		500.000+		Metals and ceramics	https://w
	Direct Laser Deposition (DLD)		High	Medium		High		High	Neutral	Metals	https://re
	Electro chemical deposition		High	Very high		High			Difficult	Metals	
	Polymer deposition		Too low								
	Digital Light Processing		Too low	High							
	Injection Moulding		High	High		High			Neutral	Injection moulding ceramics into 3D printed mould	
	Ceramic Shell Casting			Medium?		High		Low	Neutral		
Deforming	Micro-froming: Stamping			Has to be tested		Medium		Low	Neutral	For this application a new method	
	Extrusion					Low				A master die needed	
	Forging					Low				Only useable for the negative of the intended mould	
	Bending (+welding)				High	Low			Hard		
	Deep drawing			Medium		Medium					https://w
	Incremental forming			Rod has a diameter of 100 microns, which approaches but not reaches the required accuracy.							
	Superplastic forming			Has to be tested		Medium		High (prediction)		Master die needed	https://w
	Hydro-forming							High		Very interesting way of stamping	https://ar
	Hot-embossing									Metal Master die needed	
	Micro/Nano-imprinting									Master die needed	
Hybrids	Micro-Laser-ECM										
	LiGA (+laser-machining)		High	High		Mainly 2.5D				Lots of materials	https://w
	Shape Deposition + Laser machining								Difficult		
	Efab										https://w
	Laser assisted micro forming		Very high	High		Low		High	Neutral - Difficult	Mask needed	https://w
	Micro assembly injection moulding		High	Medium		Low			Difficult		https://li
	Laser machining & welding			Medium		2D layered shape					https://li
	Physical Vapour Deposition (coating)										https://w
	Micro machining + casting										
Joining	Laser-welding	Could be used in combination with "Bending".									https://w
	Resistance	Joining two materials by vibrations. Also used within Sonion. Could be used in combination with "Bending".									
	Vacuum Soldering										
	Bonding										
	Gluing										

Appendix III

Decision matrix selected methods

Initial performance estimation selected methods

Purpose of this matrix is to keep track of the findings during the validation phase on all criteria. Cells are coded green (meets criteria), orange (doesn't fully meet criteria), and blue (Not enough data to estimate). In the form seen below, most colours are estimations that are updated during the validation phase.

Information	Methods													
	CNC/EDM (Aluminium)		Microgieten (Metal)		Spuitgieten (Metaal/Ceramics)		3D printen (Plastic)		3D printen (Metal/Ceramics)		3D printen (Metal MLS)		3D printen (Addifab)	
	Pros	*Cons*	*Pros*	*Cons*	*Pros*	*Cons*	*Pros*	*Cons*	*Pros*	*Cons*	*Pros*	*Cons*	*Pros*	*Cons*
Highlights		Very expensive No straight corners	Form freedom	Shrinkage Labour intensive	Easy integration	Sintering Shrinkage		Not as durable						
Description	Traditional way of producing moulds. Creates very accurate and durable moulds.		Based on the lost wax casting method, difference is the addition of a very fine grained powder to the investment.		The available 3D printed moulds have a deflection temperature high enough for ceramic injection moulding, because ceramic particles are mixed with a binder. After moulding, the parts need sintering.		Within Sonion a lot of research has gone into the finding the right material, but no succes yet.		Very similar proces to injection moulding ceramics or metals. After printing the parts need to be sintered as well.		Very similar proces to injection moulding ceramics or metals. After printing the parts need to be sintered as well.			
Criteria*														
Temperature: nylon (270 °C) | PEEK (350-500 °C)														
Accuracy: +- 20 - 50 um tolerance			*		**									
Iteration time**	**Total**	**Active**	**Total**	**Active**	**Total**	**Active**	**Total**	**Active**	**Total**	**Active**	**Total**	**Active**		
	7h (+ iteration)*	3h*	2d	4h	1d*	2h		<1h		<1h		<1h		
Price: Reasonable	**Machine**	**Outsource**	**Machine (V/P)**	**Outsource**	**Machine (Oven)**	**Material**	**Machine**	**Material**	**Machine(Oven)**	**Material**	**Machine**	**Outsource**		
	100k+ / (15k)	15k	10K				-	~ 100 - 400 €/L			100k+	~€2.000,-		
Tool life														
Form freedom	Difficult to manufacture straight corners due to the diameter of the tool.													
Ease of execution														
Surface roughness											?			
Pressure: 300-500 bar, peak 1000+ bar***	(I.c.m Temperature)		(I.c.m Temperature)		(I.c.m Temperature)		(I.c.m Temperature)		(I.c.m Temperature)		(I.c.m Temperature)			
Notes														
*Criteria are in order of importance **Iteration time is the time it take to produce 1 sample, the method's susceptibility to iterations is not taken into account ***Important in a later stadium; might change IM accuracy and might be differ between materials	*heavily depends on the complexity of the product, how many iterations have to be done (due to unforeseen obstacles),		*Based on 3D printing accuracy		*sintering overnight **Based on 3D printing accuracy									

Figure XX: Decision matrix

Appendix IV.a

Micro casting – Initial testing

First attempt

The first casting attempt was done with a vacuum machine that managed to pull the pressure of 60 kPa. The investment powder was build up of 100% plaster and a 25/75 investment/distilled water ratio was created to make the slurry easily castable.
The result, as can be seen in figure X, captured a lot of air bubbles and air pockets but did, more importantly, replicate most (small) features of the original shape. Other than that it could be seen that the higher rectangular features had broken off.

Initial test setup

In a controlled airflow environment, the slurry is made by first mixing the required plaster quartz mixture by manually recreating the workings of a tumbling machine in a glass jar. The movements are done by hand for 5 minutes. After this, the powder is poured into a plastic casting cup where the distilled water can be added. Now, a stirring rod has to be used to form an evenly distributed slurry. After preparing the slurry, the 3D printed casting shape is inserted into the slurry from above and moved along the surface in an attempt to fill up the whole cavity.

Air bubble removal

Although the removal of air bubbles is not within the scope, the number of bubbles in the first test was too high for reliable test results. Therefore, the first efforts went into reducing the bubbles.

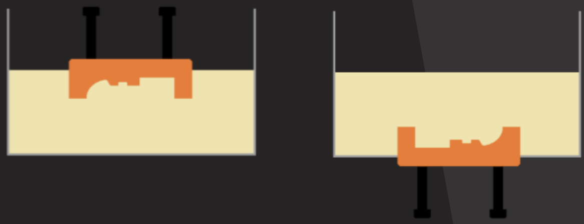


Figure XX: Initial casting setup (left) and improved setup (right)

First attempts were aiming to reduce the number of bubbles by using a vacuum chambre to pull all air out of the slurry, towards the surface. The cast was placed in the chambre before and after the casting shape was inserted.

Because the results were not as good as hoped for, some of the slurry is first applied to the to be replicated surface of the casting shape and put in the vacuum chambre together with the slurry. The setup was put in the vacuum chambre for a second time after the casting shape is put in the slurry. Results were much better although the cavity often broke off. A preliminary conclusion was that it is better to have the surface with the details facing up so the shape won't trap any air bubbles (Figure XX). This resulted in less entrapment of air and was established as the new test setup. Another advantage of this setup is that the removal of the cast shape is guided by the bottom of the cup.

Figure XX: Difference in air bubble between test 8 (left, initial cast setup), test 10 (middle, improved setup), test 33 (right, light vibrations after casting)

A last improvement on the air bubble problem is vibrating the cast, which reduces the air bubble amount and size significantly. It is assumed that an optimal casting result is acquired when vibrations and pressure regulation are combined, though it has to be investigated whether the vibrations arrange the plaster and quartz grains in a certain way. A hypothesis is that after vibrating the slurry for too long, the quartz grains either rise up or sink down due to the difference in density.

Accuracy

The accuracy of the casts is judged by sight. At the same spot for all casts, how well the layers are defined is evaluated by looking for straight corners. During the testing phase, different factors showed to have an influence on the accuracy of the replication of the casted shape:

- **Quartz/plaster ratio**: It seems that the more quartz is added, the more detailed the shape is copied. The limitation lies with the brittleness of the mould when too much quartz is added which could result in corrupted casts. No optimum in ratio is found and final casted results are acquired with a 50/50 ratio. It is predicted that a higher quartz concentration results in a higher detail.
- **Pressure vs. vacuum**: During the testing phase, both pressure and vacuum have been tested during the investing phase. It is recommended, that when investing is done in house, a vacuum/pressure/vibration investing mixer is used to invest.
- **Vibrations**: Vibrating the mixture decreases the number of bubbles significantly and increases the level of detail. Throughout the whole process, vibrations should be applied. However, shaking too much might result in an uneven mixture because liquids might rise to the surface. This effect has not been identified during the testing process, but is something to keep in mind.
- **Investment/water ratio**: A lower demi water concentration increases the level of detail, but makes the investment process more difficult resulting in the cast to be more prone to bubbles. An optimal concentration of 23 volume% seems to be found during the research.
- **Quartz grain size**: During the research, both quartz grains of 5 µm and 3 µm have been used. The 3 µm seems to replicate a higher level of detail. No significant difference in brittleness has been noticed. Besides >90% SiO_2, both powders consist of different other materials that do not have a big influence on investing, sintering or metal casting process.

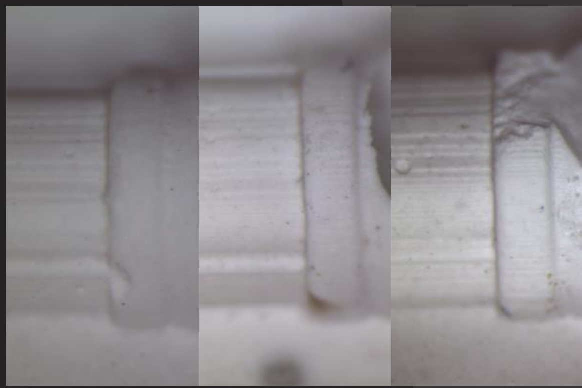


Figure XX: Left to right quarts/plaster ratio: (0,25/0,75) | (0,5/0,5) | (0,75/0,25)

Oven

All casts are sintered in the same way, following the profile in figure XX.

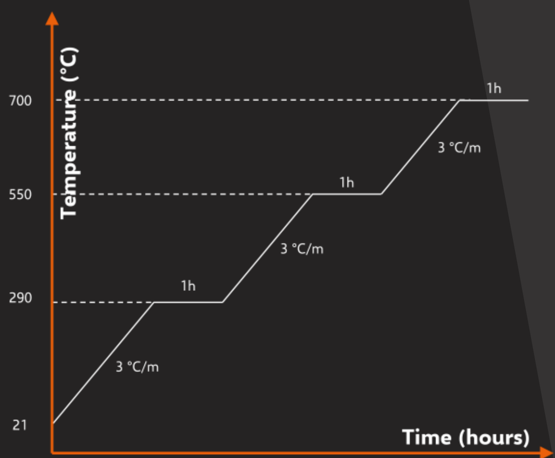


Figure XX: Investment heating profile

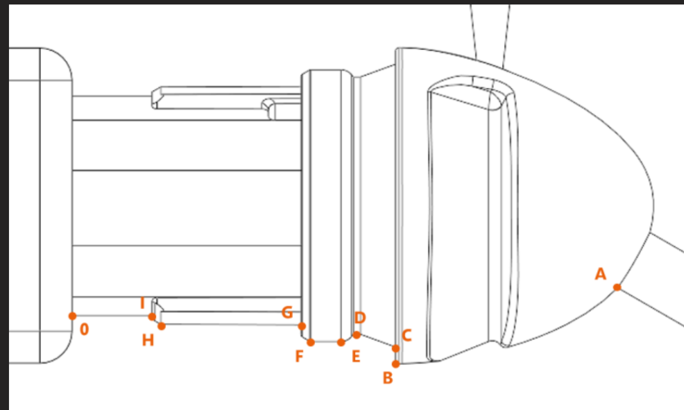
During the validation phase, the focus was not on optimising the micro casting mould as it was a proof-of-concept process. The heating profile has therefore not been optimised for metal casting.

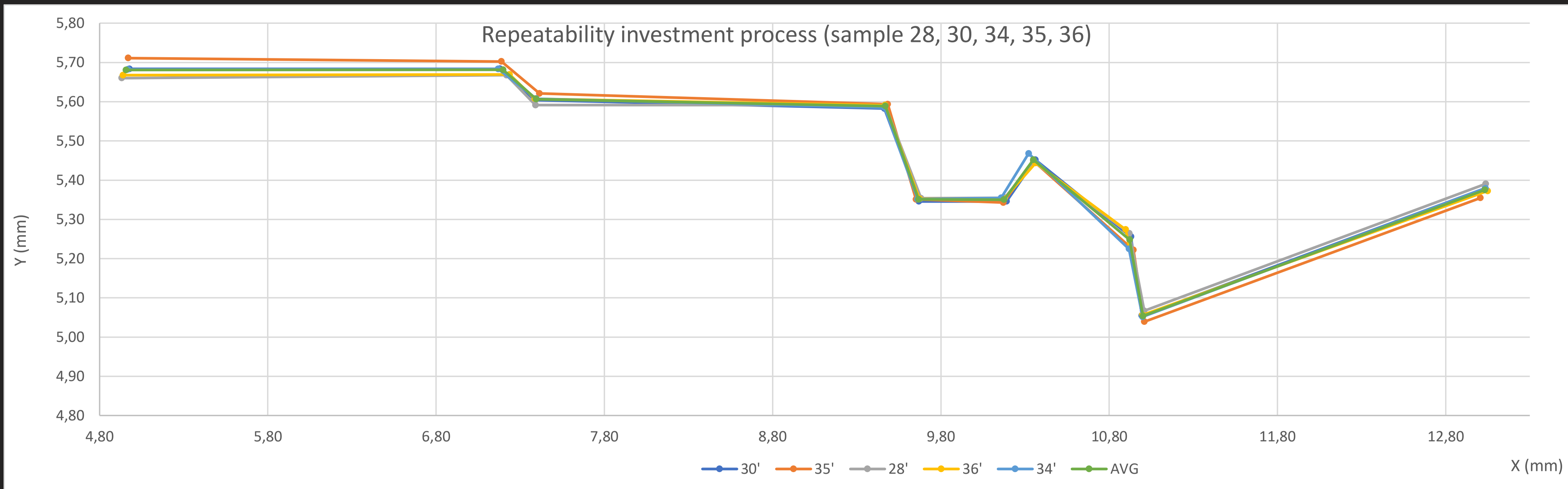
The full testing report for the investment of the micro casting method is included in appendix VIII.

Appendix IV.b

Micro casting accuracy analysis

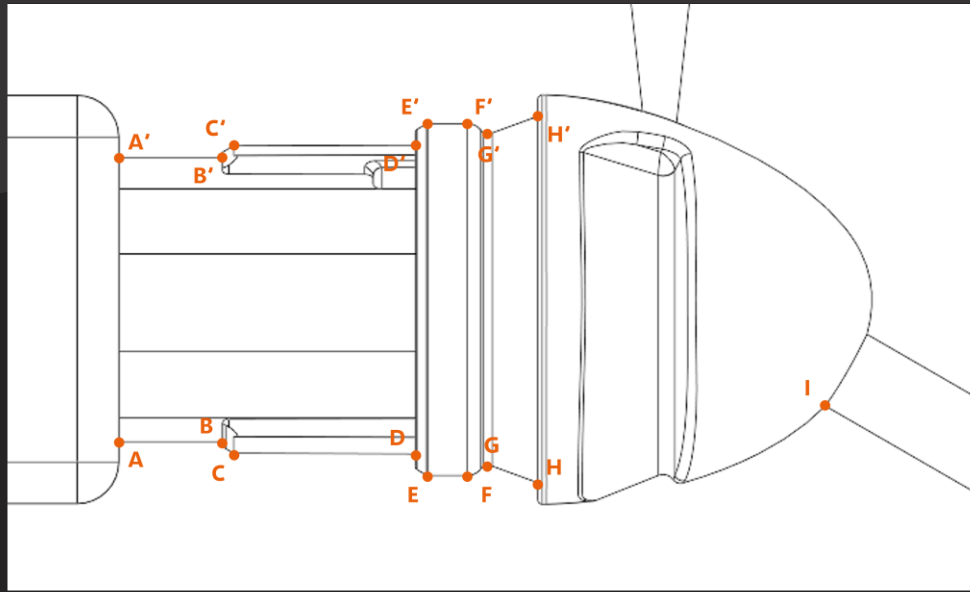
			0	I	H	G	F	E	D	C	B	A		average
Deviation	30'	X	0,020	-0,019	-0,007	-0,006	0,002	0,015	0,011	0,008	-0,008	0,003		0,010
		Y	0,003	0,002	-0,002	-0,006	-0,005	-0,005	0,000	0,008	0,001	0,004		0,004
	35'	X	0,013	-0,010	0,019	0,014	-0,015	-0,004	0,000	0,022	0,008	-0,027		0,013
		Y	0,030	0,021	0,015	0,005	0,000	-0,007	-0,002	-0,026	-0,015	-0,021		0,014
	28'	X	-0,027	0,020	-0,004	-0,002	0,015	0,004	0,003	-0,002	0,007	0,005		0,009
		Y	-0,021	-0,014	-0,015	0,003	0,003	0,005	-0,005	0,016	0,013	0,015		0,011
	36'	X	-0,018	0,038	-0,008	-0,002	0,005	0,002	0,013	-0,024	-0,004	0,016		0,013
		Y	-0,013	-0,012	0,001	0,002	0,002	0,003	-0,008	0,026	0,003	-0,003		0,007
	34'	X	0,012	-0,029	0,000	-0,005	-0,006	-0,017	-0,028	-0,004	-0,003	0,003		0,011
		Y	0,001	0,002	0,001	-0,004	0,001	0,004	0,016	-0,024	-0,002	0,004		0,006
														0,010

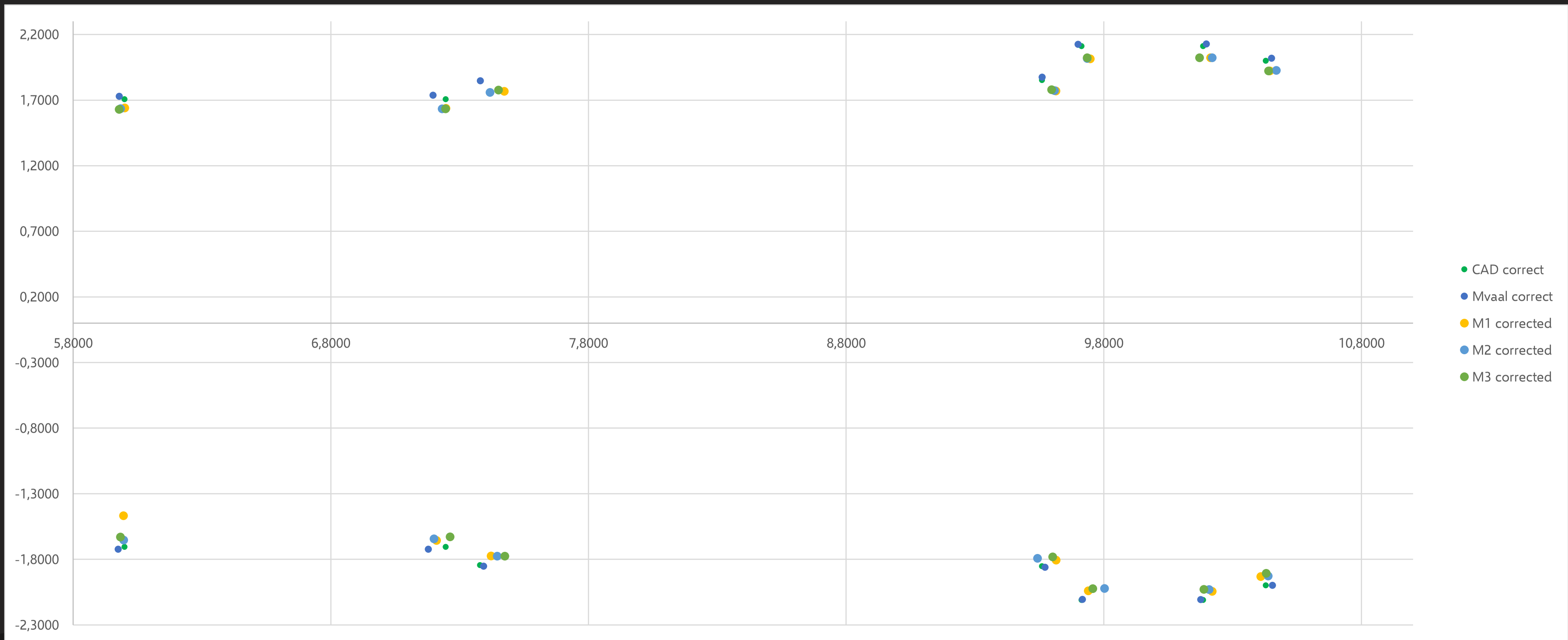




Appendix IV.c

Micro metal casting accuracy test result (plot), and reference points





Appendix IV.d

Micro metal casting accuracy test result (data)

Metal casting notes

- The reason the surfaces on the cast are not fully planar is because the 3D printed cast shapes were not planar. This is not due to a non-uniform shrinkage behaviour.
- Some of the higher deviation values might be due to errors in the measuring process. For a proper comparison in geometrical accuracy, it is suggested to do a more advanced analysis.

		A	A'	B	B'	C	C'	D	D'	E	E'	F	F'	G	G'	H	H'	H2	H2'	I	Average
Mvaal	X	6,0040	6,0003	7,2223	7,2041	7,4057	7,4182	9,5861	9,5971	9,7252	9,7425	10,2234	10,2012	10,4766	10,4798	11,0416	11,0588	10,9968	10,9959	14,5363	
	Y	4,7777	8,2292	4,7691	8,2291	4,6592	8,3593	4,6322	8,3676	4,3807	8,6122	4,3788	8,6135	4,4870	8,5049	4,2847	8,7262	4,3179	8,6785	5,2069	
M1	X	5,9104	5,9153	7,1132	7,1496	7,3230	7,3735	9,4939	9,4937	9,6179	9,6255	10,0941	10,0873	10,2805	10,3153	10,8818	10,9238				
	Y	4,9744	8,0508	4,7866	8,0488	4,6702	8,1764	4,6387	8,1799	4,4078	8,4218	4,4034	8,4302	4,5152	8,3308	4,3176	8,5516				
M2	X	5,8956	5,8837	7,0877	7,1191	7,3307	7,3031	9,4070	9,4723	9,6644	9,5980	10,0665	10,0783	10,2932	10,3242	10,9109	10,9104				
	Y	4,8098	8,0652	4,8192	8,0640	4,6885	8,1879	4,6717	8,2014	4,4443	8,4439	4,4357	8,4500	4,5377	8,3548	4,3276	8,5594				
M3	X	5,9065	5,9018	7,1734	7,1560	7,3835	7,3590	9,4888	9,4848	9,6429	9,6214	10,0699	10,0533	10,3092	10,3179	10,9254	10,9318				
	Y	4,8173	8,0454	4,8194	8,0496	4,6730	8,1905	4,6683	8,1942	4,4288	8,4356	4,4226	8,4352	4,5439	8,3360	4,3246	8,5585				
Average	X	5,9291	5,9253	7,1492	7,1572	7,3607	7,3635	9,4940	9,5120	9,6626	9,6469	10,1135	10,1050	10,3399	10,3593	10,9399	10,9562				
	Y	4,8672	8,0538	4,8084	8,0541	4,6772	8,1849	4,6596	8,1918	4,4270	8,4338	4,4206	8,4385	4,5323	8,3405	4,3233	8,5565				
Average - M1C	X	-0,004	-0,013	0,014	-0,005	0,026	-0,026	-0,028	-0,008	0,027	-0,008	-0,015	-0,012	0,017	0,007	0,027	0,001				**0,015**
	Y	0,116	0,005	-0,014	0,003	0,001	0,000	-0,013	-0,004	-0,011	-0,004	-0,009	0,000	-0,009	-0,002	0,002	0,003				**0,012**
Average - M2C	X	-0,005	0,004	0,024	0,009	0,002	0,029	0,044	-0,002	-0,036	0,004	-0,003	-0,019	-0,012	-0,018	-0,018	-0,001				**0,014**
	Y	-0,069	0,000	-0,001	-0,002	0,000	-0,009	0,001	-0,002	0,006	-0,001	0,004	0,000	-0,006	0,003	-0,007	-0,009				**0,007**
Average - M3C	X	0,008	0,009	-0,039	-0,004	-0,028	-0,003	-0,015	0,009	0,009	0,004	0,018	0,030	-0,004	0,012	-0,009	0,001				**0,013**
	Y	-0,047	-0,005	0,014	-0,001	-0,001	0,009	0,012	0,006	0,005	0,005	0,005	0,000	0,015	-0,001	0,005	0,005				**0,009**
																					0,012
CAD - Vaal	X	0,021	0,025	0,049	0,067	-0,002	-0,014	-0,001	-0,012	0,014	-0,003	-0,012	0,010	-0,023	-0,026	0,015	-0,002				**0,018**
	Y	-0,022	0,018	-0,030	0,018	-0,001	0,009	-0,021	0,009	-0,014	-0,004	-0,016	-0,003	-0,020	-0,001	-0,022	0,022				**0,014**

Appendix IV.d

Relation between cast deviation and wax cast shape geometry

MC1 => M1C
MC2 => M2C
MC3 => M3C.

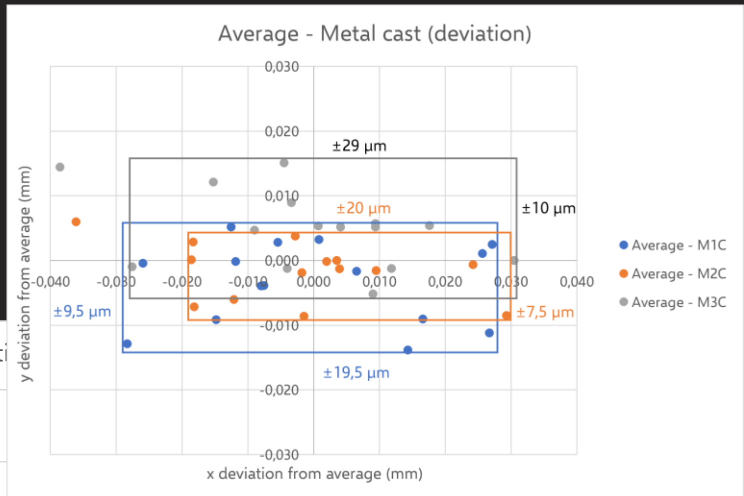


Figure: Deviation metal casts

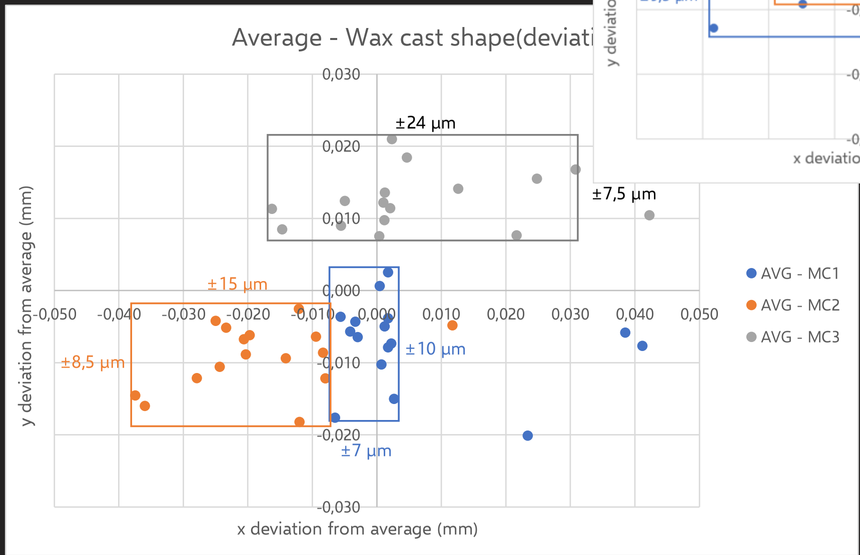


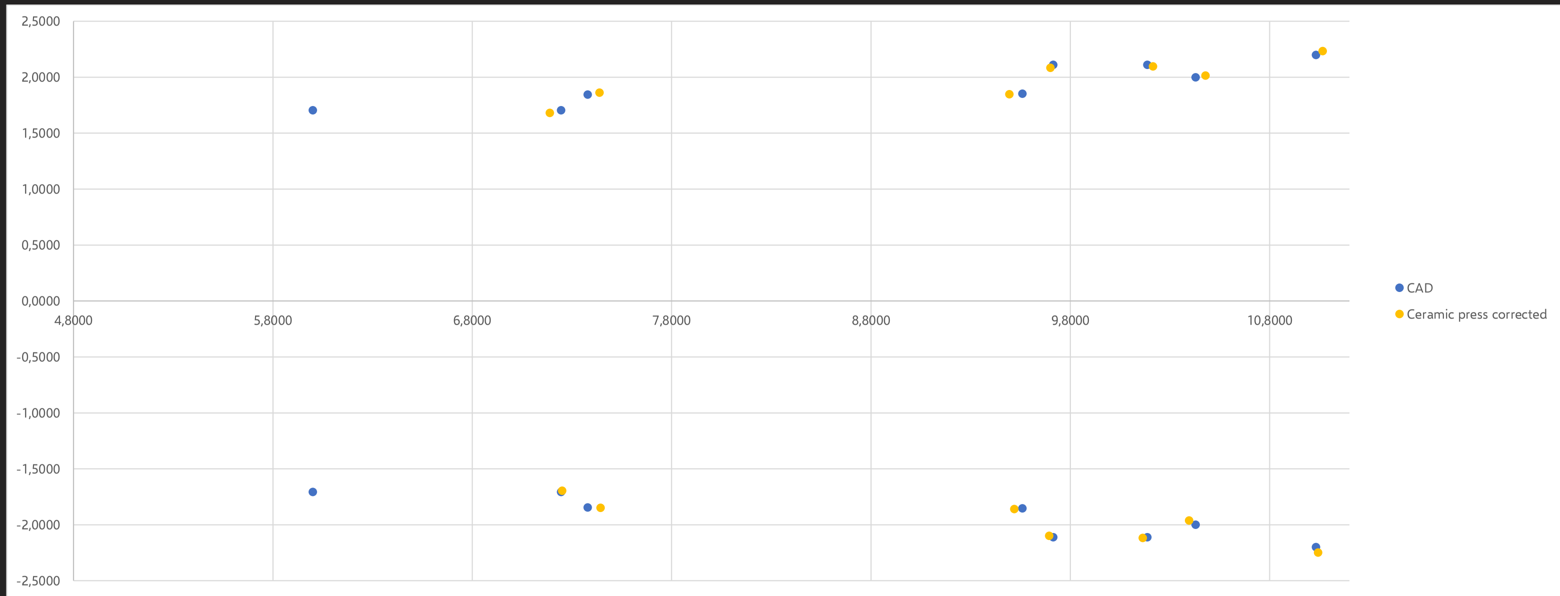
Figure: Deviation 3D printed wax cast shapes

Relation cast deviation and wax cast shape geometry

To some extend, a relation between the average deviation of the wax cast shape and the average deviation of the metal casts can be seen. When the tolerance is placed in order from biggest to smallest, the order for both shapes corresponds, namely shape 3 to 1, with one exception being the X tolerance of shape 1. Therefore, a relation between the accuracy of the cast shape and the metal cast is found. However, the deviation is magnified in the metal casting step.

Appendix V

Geometrical analysis Ceramic Pressed part



		A		B		C		D		E		F		G		H		I
CAD	X	6,0000	6,0000	7,2460	7,2460	7,3790	7,3790	9,5600	9,5600	9,7140	9,7140	10,1860	10,1860	10,4290	10,4290	11,0320	11,0320	
	Y	-1,7061	1,7059	-1,7061	1,7059	-1,8451	1,8449	-1,8521	1,8529	-2,1111	2,1109	-2,1111	2,1109	-1,9991	1,9999	-2,1991	2,1989	
Ceramic press	X			7,2510	7,1893	7,4434	7,4387	9,5193	9,4942	9,6943	9,7005	10,1638	10,2145	10,3957	10,4784	11,0433	11,0656	
	Y			-1,6942	1,6818	-1,8481	1,8629	-1,8584	1,8487	-2,0983	2,0850	-2,1165	2,0970	-1,9614	2,0146	-2,2470	2,2340	
Deviation	X			0,005	-0,057	0,064	0,060	-0,041	-0,066	-0,020	-0,014	-0,022	0,028	-0,033	0,049	0,011	0,034	
	Y			0,012	-0,024	-0,003	0,018	-0,006	-0,004	0,013	-0,026	-0,005	-0,014	0,038	0,015	-0,048	0,035	

Appendix VI.a

Final decision matrix

Information	Methods (Mould Fabrication)													
	IM Team Sonion				Mathijs									
	CNC (Aluminium)		3D printen (Plastic)		Microgieten (Metal/Ceramics)		Poeder Spuitgieten		3D printing (Metal/Ceramics)		Direct Metal Printing		Zirconium CNC	
	Pros	*Cons*	*Pros*	*Cons*	*Pros*	*Cons*	*Pros*	*Cons*	*Pros*	*Cons*	*Pros*	*Cons*	*Pros*	*Cons*
Highlights		Very expensive		Not as durable	Form freedom	Shrinkage	Easy integration	Sintering						
		No straight corners				Labour intensive		Shrinkage						
Description	Traditional way of producing moulds. Creates very accurate and durable moulds.		Within Sonion a lot of research has gone into the finding the right material, but no succes yet.		Based on the lost wax casting method, difference is the addition of a very fine grained powder to the investment. Both for metal micro casting as ceramic hot pressing.		The available 3D printed moulds have a deflection temperature high enough for ceramic injection moulding, because ceramic particles are mixed with a binder. After moulding, the parts need sintering.		Very similar proces to injection moulding ceramics or metals. After printing the parts need to be sintered as well.		Very similar proces to injection moulding ceramics or metals. After printing the parts need to be sintered as well.		Outsource	
Criteria*														
Temperature: nylon (270 °C) | PEEK (350-500 °C)														
Accuracy: +- 5-20 um tolerance			±10 um		±25 um		<±30 um		±20 um (when outsourced)		±50 um / ±1 um build volume too small		Smallest diameter 0.3 mm	
Iteration time**	**Total**	**Active**	**Total**		**In-house**	**Outsource**	**Total**	**Active**	**In house**	**Outsource**	**In house**	**Outsource**	**Total**	**Active**
	7h (+ iteration)*	3h*	<1h		2-3d	1-2 weeks	1d*	2h	1d / <1h	6+ weeks		2 weeks	3d	0
Price: Reasonable	**Machine**	**Outsource**	**Machine**	**Material**	**Machinery**	**Outsource**	**Machine (Oven)**	**Material**	**Oven/material**	**Outsource**	**Machine**	**Outsource**	**Outsource**	
	100k+ / (15k)	15k	-	~ 100 - 400 €/L	€20k	€170	€9k		-	~€600	100k+	~€2.000,-	€4000/p *	
Tool life			~10 shots											
Form freedom	Difficult to manufacture straight corners due to the diameter of the tool.													
Ease of execution														
Surface roughness											2-3 um			
Pressure: 300-500 bar, peak 1000+ bar***	(I.c.m Temperature)		(I.c.m Temperature)		(I.c.m Temperature)		(I.c.m Temperature)		(I.c.m Temperature)		(I.c.m Temperature)		(I.c.m Temperature)	
Notes														
*Criteria are in order of importance **Iteration time is the time it take to produce 1 sample, the method's susceptibility to iterations is not taken into account ***Important in a later stadium; might change IM accuracy and might be differ between materials	*heavily depends on the complexity of the product, how many iterations have to be done (due to unforeseen obstacles),				*Based on 3D printing accuracy		*sintering overnight **Based on 3D printing accuracy		Outsourcing takes too much time due to the low tolerance. The sintering phase for the lithoz method takes 2 weeks alone, their whole proces takes 6 weeks + 2 weeks for each iteration. Besides this, it is safe to say that a tolerance close to ±20 um won't be reached in house if it takes that long for experienced companies.				*The cost is higher when compared to a part the laboratories normally make because of the unconventional shape and low tolerance. This method is dicarded because the accuracy requirements can't be met and due to the high price.	

Appendix VI.b

Cost and iteration time estimations

Cost						Iteration time			
*Estimations are made based on one halve of a RIC insert mould				Cost	Per Part	Action	Time (h)		Realistically
Microcasting	In-house	Material	Casting wax resin	€ 150/L	€ 10				
			Plaster	(20kg) €74,95	€ 1				
			Quartz	(1kg) ~€75	€ 10				
			Metal	(1kg) ~€20	€ 1	Over night			
		Personel	Printing	(0.5h)	€ 120				
			Investment	(2h)		Printing	4		
			Casting	(0.5h)		Investment casting	2		
			Cleaning	(0.5h)		Drying	3		
		Investment	Vacuum/pressure casting machine	~€ 15.000		Oven	8		
			Investing machine (optional)	~€ 2.000		Cast	0.5		
			Oven	~€ 2.000		Clean	0.5		
			Total	€ 20.000	€ 122	Total	17	h	2-3 days
	Out-source		Total price	€ 180		Delivery in	1 week		
Ceramic 3D printing	In-house	Material	Ceramic resin	€ 150/L	€ 10				
		Personel	Printing	(0.25h)	€ 20				
			Oven	(0.25h)		Printing	4		
		Investment	Oven	~€ 9.000		Oven	10		
			Total	€ 9.000	€ 30	Total	14	h	1 day
	Out-source		Total price			Delivery in	4+ weeks		
Injection moulding	In-house	Material	Feedstock	?	?				
		Personel	Printing	(0.25h)		Printing	4		
			Moulding	(3h)		Moulding	3		
		Investment	Oven	~€ 9.000		Oven	10		
			Total	€ 9.000	?	Total	17	h	1-2 days
Ceramic hot pressing	In-house	Material	Casting wax resin	€ 319/L	€ 10				
			Plaster	(20kg) € 74,95	€ 1				
			Quartz	(1kg) ~€75	€ 10				
			Ceramic ingots	€ 20 /ingots	€ 40	Printing	4		
		Personel	Investment	(2h)	€ 100	Investment casting	2		
			Casting	(0.25h)		Drying	3		
			Cleaning	(0.5h)		Oven	8		
		Investment	Ceramic press	€ 8-10.000		Cast	0.25		
			Oven	~€ 2.000		Clean	0.5		
			Total	€ 12.000	€ 161	Total	17	h	2-3 days
3D printing	In-ho	Material	High temperature resin	€ 400/L	€ 25				
		Personel	Printing	(0.25h)	€ 10	Printing	4		
			Total			Total	4	h	1 day
	Out-source		Total price			Delivery in	4 days		
CNC milling	In-house	Material	Aluminium		?				
		Personel	CNC trail and error	(6h)	?	Simulation	4		
		Investment	CNC machine	€ 100.000+	?	CNC trail & error	24		
			Total	€ 100.000+	?	Total	28	h	5 days
	Out-source		Total price		€ 15.000	Delivery in	6 weeks		

Appendix VII

Project brief

Efficiency optimisation of the prototyping process for injection molding

project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 13 - 02 - 2023

30 - 06 - 2023 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

This project takes place at the company Sonion, a global leader in designing and manufacturing components and solutions for hearing instruments to improve people's quality of life. The company has one branch in Hoofddorp, the Netherlands. Within this facility new technologies for hearing aids are developed in a prototype intense manner. Production of the hearing aids is done in Asia. These prototypes are made very precisely, with a tollerance between 20 and 50 um. This research focusses on the prototyping process within the company.

Because of the small scale of their devices, testing has to be done very accurately. Therefore, the goal is to make prototypes that come as close as possible to the the final product. This is done so that testing results of these prototypes approach the performance of the actual product. It is a biocompatible process, the prototyped parts should be wearable and should be able to withstand skin contact. In order to do this as efficiently as possible it is preferred to make the whole prototype and all its requisites in house. An injection moulding machine is used to produce a relatively small amount of parts that have properties that are almost equal to parts from the factory. The production of these moulds had to be outsourced which costs a lot of money but more importantly adds a lot of time between each iteration step.

The stakeholders within Sonion are the designers, the people that will produce and use the mould, the suppliers of all used products and Sonion as a company itself. This project will mainly focus on the people that will actually work with the moulds, but with all the financial aspects it will also be benificial for Sonion.

A very valuable improvement for this process would be to find a way to produce these moulds more time and cost efficiently. A good way to do this might be with the use of 3D printers.
Possible opportunities could be;
Printing the moulds out of ceramics. Disadvantage of this is the shrinkage that occurs during the post processing.
Making dissolvable moulds. This takes away the need of split lines and sliders and therefore their tolerances.
Making moulds with CNC machining.
Investment casting, permanent mould casting, composite casting or resin casting. (Tang et al., 2007)
SLM printing of a metallic microstructured mould, traditionally used for plastic microfluidic devices.
Laser Powder Bed Fusion printing (Awad et al., 2021) or Direct Metal Laser Sintering to print metal moulds.

At the moment they have a wide range of tools and machinery at their facility in Hoofddorp. Besides an assembly machine, injection moulding machine and a CNC machine they have a state of the art resin 3D printer and several high end consumer resin printers. Because of the small layer height and the high accuracy of these machines there is no need for any post processing other than curing.

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introduction (continued): space for images

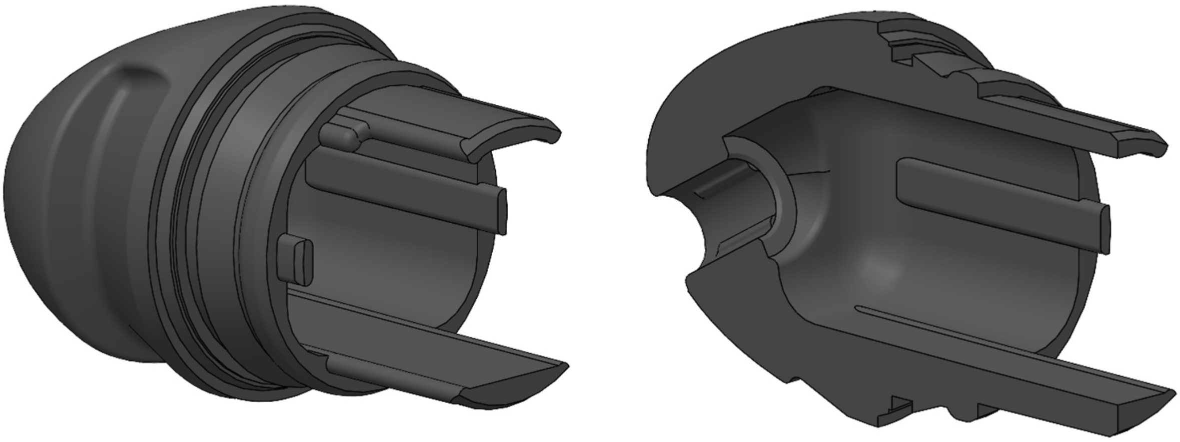


image / figure 1: Exemplary parts to be injection molded

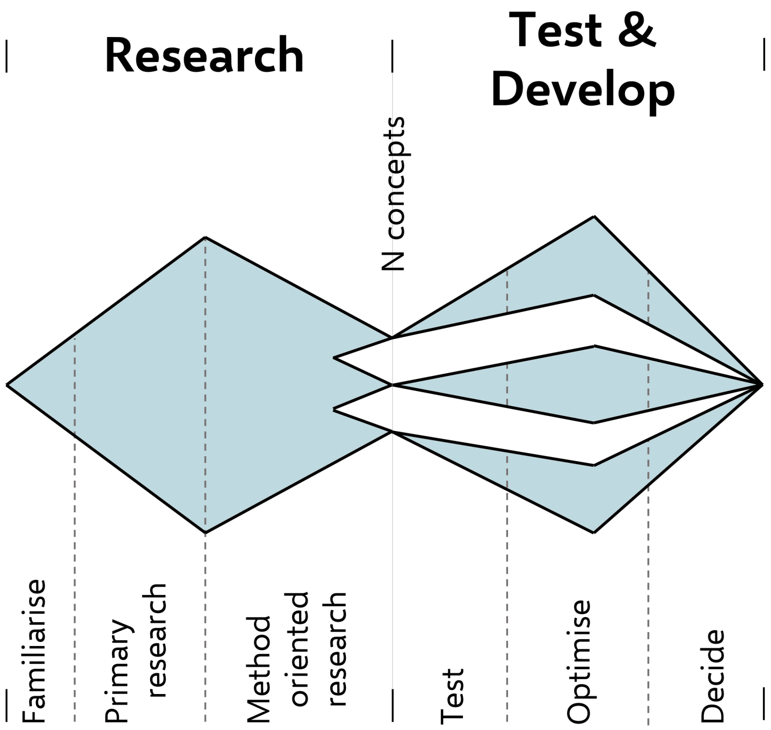


image / figure 2: Method: Double Diamond

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

The general problem to be tackled is to increase the quality and functionality of the prototypes so that the properties of the prototype resemble those of the final product as close as possible. In the past the moulds had to be outsourced to other companies, where they would be made from steel with a CNC machine. This is not only too expensive but also takes too much time. Therefore, the main goal of the project is to come up with a way to produce moulds for the injection moulding machine. In short, the factors to be improved are time, accuracy and cost, also in this order, of the prototyping process. Production can be either in house at the Sonion facility in Hoofddorp or a collaboration with a company that focusses on mould production.

For the production of the moulds, the focus will be on 3D printing since this is the most promising method. Other methods will be considered as well. To discover new technologies, other fields will be researched where they work with similar limitations. For instance, fields that might be of interest could be the technical side of the medical field and the production of semi conductors.

Furthermore, the prototyping and development process as a whole will be evaluated to consolidate the necessity of the project, to give new input to the project or to redirect the project. Questions that arise are: Could other improvements be made so that testing can be done more efficiently? Are there other ways to test certain aspects of the design?

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

Designing a method for the production of moulds for the injection moulding machine to make the prototyping process of hearing aids more efficient. The three aspects that should be optimised are cost, time and accuracy.

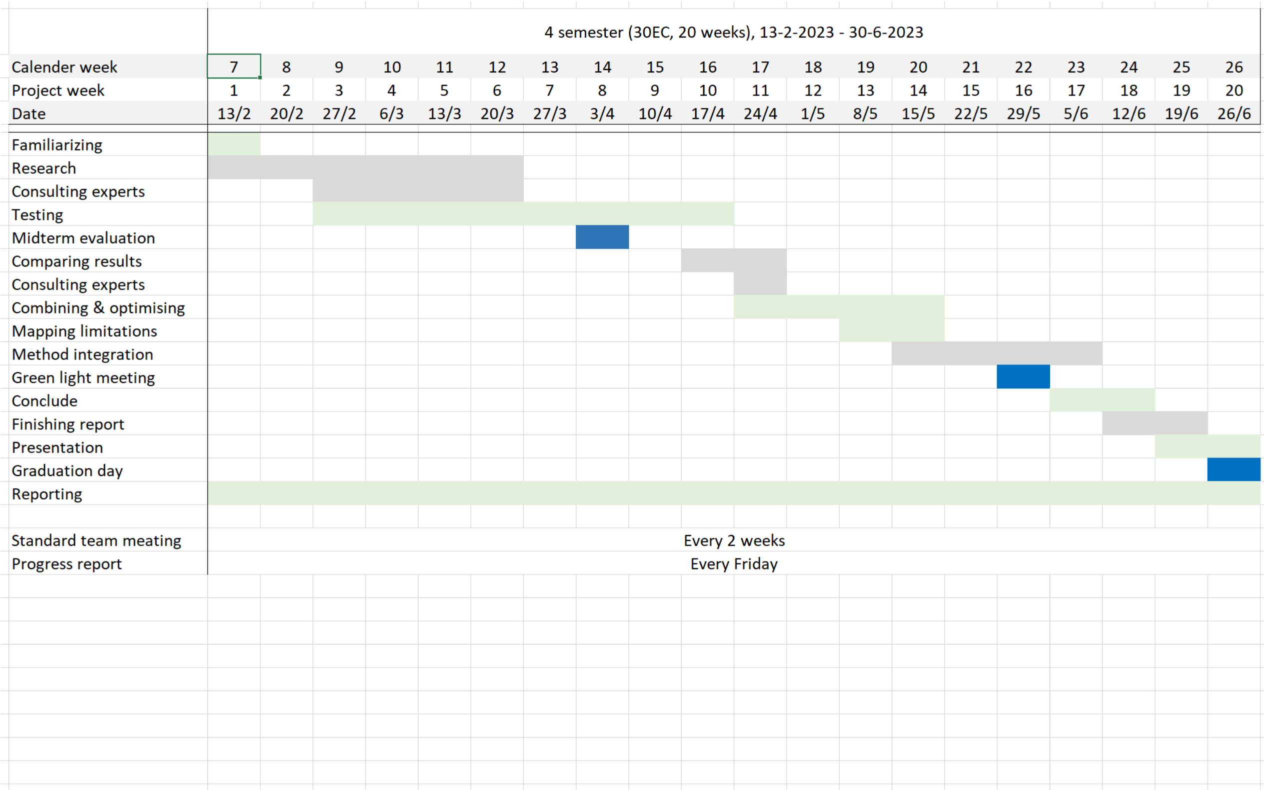
The main goal of the project is to come up with a way to produce moulds for the injection moulding machine. The solution is in the form of a method. This method can be integrated at the facility in Hoofddorp and is able to improve the prototyping process within the company. The method will consist of 2 parts, namely the practicle part of how to produce the moulds, as well as a guide on how it can be integrated as seamlessly as possible. By the end of the project, a proof of concept will be delivered.
The main aim of this concept is to decrease the time it takes to acquire the mould, which is 4 to 8 weeks currently. Decreasing the time cannot hinder the tolerance of the mould, this should be below ±50um but preferably below ±20um.
The price of one mould is between $10K to $15K, this is without taking the time loss into account. This price should be lowered.
The goal is to meet all 3 targets with a high priority on reducing the production time. Outsourcing the production of the mould more efficiently could be a possible solution as well or could be used as a benchmark.
At this point in time, 3D printing of the moulds is a very promising way of production due to their high accuracy but are limited in their heat and pressure resistance.

Optimising the efficiency of the prototyping process involves more than just creating a new method, therefore the process of prototyping and testing will also be evaluated to see if there might be more suitable methods for the development of new designs. Part of my results could be recommendations within the process.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 13 - 2 - 2023   30 - 6 - 2023 end date



The project will start off at the 13th of February with a period of getting familiar with the process, the company and the employees. Simultaneously, online and literature research will be conducted. Different ways of manufacturing the moulds will be found and bridges to other industries might be discovered and applied as well.
During the 6 week research phase, testing of the found methods starts at the 27th of February. Quickly after a promising method is found and analysed, the materials that are needed will be ordered. This is done to make sure as many different methods as possible can be put to the test. Before ordering, experts are consulted to see what they think of the test and consider it viable and feasible.In week 8 the midterm evaluation is planned.
On the 17th of April it is expected that most of the possible methods have been tested. At this point, the results will be compared to eachother and experts from Sonion and the TU Delft will be consulted. At the end of this 2 wek period week, a conclusion will be formed that will direct the rest of the project.
From week 11 onwards, the most promising method(s) will be combined, if possible, into one method and then this method will be optimised and prepared to be integrated into the prototyping process. During this phase, the method will be used for different types of applications and will be calibrated accordingly. Half way through this 4 week period, the limitations of the method will be mapped out as a foundation for the integration phase.
From the 15th of May, the method will be integrated for 4 weeks as fittingly as possible in the workflow of Sonion. In this period, in week 16, there will also be the green light meeting. After week 16, the process will be concluded and the final version of the report will be started on the 12th of June. At the start of week 19 shaping the presentation will be started and at the end of that week the report and all appendices have to be handed in.
Bi-weekly meetings with the team will be scheduled and progress reports will be send by the end of every week to the team.

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

As a person I have always been interested in working on a small scale. While designing, I try to make a design as small as possible. On top of that, I really enjoy making my designs come to life with a 3D printer. Because of this, I'm quite comfortable working with FDM 3D printers. However, in order to print on a small scale with a lot of detail a resin printer is required, a printer I have been wanting to work with for a long time.
Also, since I started working with 3D printers I have been fascinated by the idea of printing moulds for casting, which was more suitable for "do it yourself" projects at home, or injection moulding. Because of this, I have also looked into centrifugal casting for example. 3D printing can be used really well to prototype one piece, but once a more substantial amount of parts has to be produced it takes too long.

As can be concluded from the text above, I am more of a technical designer. This can also be related to my history in mechanical engineering. I'm very motivated to work on designs that have a (complicated) function while making sure the aestethics and ergonomics are also taken into account. This project is on this more technical side of designing and I'm looking forward to it pushing my knowledge and skills. Although I have experience with prototyping with 3D printers, printing on this small scale and with these restrictions will take my abilities to the next level.

For the last couple of years I have been looking forward to working in a company and experiencing how projects outside of the university take place. I'm curious to see how designers collaborate in companies and how knowledge is exchanged.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

Tang, Y., Tan, W., Fuh, J., Loh, H., Wong, Y., Thian, S., & Lu, L. (2007). Micro-mould fabrication for a micro-gear via vacuum casting. Journal of Materials Processing Technology, 192 – 193, 334 – 339. https://doi.org/10.1016/j.jmatprotec.2007.04.098
Awad, A., Fina, F., Goyanes, A., Gaisford, S., & Basit, A. W. (2021). Advances in powder bed fusion 3D printing in drug delivery and healthcare. Advanced Drug Delivery Reviews, 174, 406 – 424. https://doi.org/10.1016/j.addr.2021.04.025

Appendix VIII

Investment testing report – micro casting

Microcasting

Investment casting accuracy factors:

- Casting alloy
  - High form filling ability
  - Flowability of the melt

    Both are influenced by
    - Viscosity of the melt
    - Wetting behaviour of the form
    - Reaction with the mould and the atmosphere
    - Solidification behaviour
- Ceramic investment
  - Phosphate bonded
  - Plaster bonded

    Investment modification (better roughness):
    - Coating
    - Infiltrating the mould (small effect)
    - Adding filler
- Preheating the mould
- Casting pressure

List of materials

Casting alloys

- Stabilor G
- Al-bronze

  8.5-11 wt% al, 4-6 wt% Ni, 2-5 wt% Fe, copper base
- CoCrMo-alloys

Filler

- Quartzwerke, SF 800

  http://www.hpfminerals.kr/images/uploads/Datenblaeter/Cristobalite/1304-SIKRON-CR-de-en.pdf (SF 8000)
- Quartzwerke, SF 795

Base

- Phosphate-bonded material, DeguvestCF from Degussa AG
- Superhartgips, Finostone, Plaster

Tools

- Vacuum pressure casting machine
  Prestomat, Degussa Dental GmbH
- Embedding process supported by light vibrations (vacuum mixer)
  Multivac 4 Degussa Dental
- Ultrasonic bath for plaster removal?
  Chemicals for plaster removal?
- Superhartgips, Finostone (commercially available)

Needed:

Test phase 1:

- Filler: SIKRON SF800 from Quartzwerke.
  (or something similar; Upper grain size $d_{95\%}$=6 um, Average grain size $d_{50\%}$=2 um)
  Datasheet: http://www.hpfminerals.kr/images/uploads/Datenblaeter/Silica/1205-SIKRON-Quarz-HPF.pdf
  https://www.moertelshop.eu/buy-silica-fume-white-cheaply_4
  https://stynenminerals.nl/kwarts-silica-siliciumdioxide-sio2-0
- Superhartgips, Finostone, Plaster
  https://www.dt-shop.com/index.php?id=22&L=6&artnr=11840P&aw=203&pg=3
- Phosphate-bonded material, DeguvestCF from Degussa AG
- Oven

Test phase 2:

- A vacuum/pressure casting machine; tests at a different company
- Casting alloy: Al-bronze; 8.5-11 wt% Al, 4-6.5 wt% Ni, 2-5.5 wt% Fe, copper base
- Mould sprue orientation can be tested as well as preheat temperatures of the mould

Test phase 3:

- A vacuum/pressure casting machine

Test plan (phosphate bonded)

Test plan for casting with a phosphate bonded investment.
Different aspects can be tested:

- Baking the 3D print out
- Different investment ratios

Baking of 3D print test

- Steadily increase the temperature up to a different temperatures around the melting point
- Wait 15 minutes
- See how much has been liquified

Mould test

- Thick negative of the mould
- Make different types of investment
  Vary in water/liquid, liquid/powder and heating steps
- Create moulds
- Bake
- Saw in half and inspect

Obstacles

- How to test how to bake out the 3D print.
- Normally the mould goes from the oven straight into the casting machine. How much will the mould change when I wait and cut it open.

1. Figure out how to bake out the 3d print
2. Cast a mould around it
3. See what the mould looks like
4. Modify the investment by adding quartz

Available quartz powders

Reference quartz powder from research papers

SiO2	Fe2O3	Al2O3	MgO + CaO	K2O + Na2O	White	Dens	Mois	Hard
97.5	0.05	2.9	0,1	0,1	92	2.45	<0.12	7

(DS) D_{50} = 2 um , D D_{50} = 2,9 um

(DS) D_{95} = 6 um

Stynen 40Si5 powder

PARTICAL SIZE

Product Type		40Si1	40Si5	40Si17	40Si32
D10	µm	0,4	1,7	3,5	5,0
D50	µm	1,7	4,8	17,8	33,5
D90	µm	4,2	11,0	44,0	98,0

PROPERTIES (all types)

Refractive Index		1,55
Hardness	Mohs	7
Sintering	^{o} C	1.600
pH Value		7
Density	kg/dm^3	2,65
Los on Ignition	%	0,2

CHEMICAL ANALYSIS

Silicon Dioxide	SiO_2	99,5 %
Aluminium Oxide	Al_2O_3	0,13 %
Iron Oxide	Fe_2O_3	0,03 %
Titanium Dioxide	TiO_2	0,02 %

US Nano quartz powder (3um)

Size	SiO2	Fe2O3	Al2O3	MgO2	K2O	Oil ab	PH	White	Dens	Mois	Hard
3um	>99.5	0.025	0.09	0.02	0.064	32.2	7.0	92	2.45	<0.12	7

First test plan

This is the order in which the micro casting tests will be conducted. Down below an overview of the used materials can be seen. First test will be a first attempt of casting. There won't be any ratio changes of binder, filler, expansion liquid and water. For the first test, the ratios will be copied from online research and the manufactures casting guide. This will be the starting point of the test phase, from these results a more clear plan will defined.

Test intention

In this test, the first casting steps will be made. It can be seen as more of a practice run than a official test. Besides the results of mixture differences, other results are expected concerning the process. Unclear factors in the process are: attachment of the slurry to the cup and casting shape, removal of the cup from the solidified slurry (after 20 minutes), mixing the powders and the liquid, possible existence of air bubbles, but there will also be a focus on action optimalisation and becoming more skilful.

Materials

- Binder
  - Finostone Superhartgips (Plaster)
  - GC Fujivest Platinum II (Phosphate bonded)
- Filler
  - Stynen 40Si5 (Quartz Powder D_{50}=5um)
- Liquid
  - Distilled water
  - GC Fujivest Platinum Liquid (Expansion Liquid)
- Plastic container
- Masker
- Oven
- Knife
- Vacuum machine
- Mixing cup
- Closable cup
- (Drum hoop stirring machine)

Initial test

Two initial tests will be conducted, one with the plaster binder and one with the phosphate bonded binder. This test will use the slurry ratio of online research [XX] and the guide as the manufacturer provides it.

Phosphate bonded

According to the guide, the perfect mixture of investment powder and liquid (gr/ml) is 0.820:0.180. The liquid is made up of distilled water and an Expansion Liquid. The expansion liquid should be diluted by the distilled water based on what type of metal is used. The purpose of the expansion liquid is to compensate for the shrinkage of the metal, so the ratio depends on what type of metal will be casted. In other words, because the chosen metal will be an aluminium bronze alloy which is not in Fujivest's guide, the right ratio has to be found empirically. For the first test, the standard ratio liquid:dist water (1:2) will be kept.

	Investment powder		Liquid	
	Fuijvest Platinum (g)	Quartz	Fuijvest liquid (ml)	Dist. Water (ml)
1	30	-	2.2	4.4
2	20	10	2.2	4.4
3	10	20	2.2	4.4

The slurry is dried for 3 hours before it is place in the oven.

Step heating

	Room °C	Time (mins)
	260 °C (3°C/min)	87
Holding	60 - 90 mins	75
	580 °C (5°C/min)	64
Holding	20-50 mins	35
	750 - 800 °C (5°C/min)	19
Holding	30 mins	30
		310

Plaster

The plaster investment only has to be mixed with distilled water. This material did not come with a guide, but is used in a variety of different papers. In these papers, experiments have been conducted to optimise the surface roughness and the detail of the mould and the final metal product. Water contents have been varied between 21% and 30%, by weight. For the first test, the water content will be kept the same (25 weight%) throughout all tests.

	Investment powder		Liquid
	Plaster (g)	Quartz (g)	Dist. Water (g)
1	30	-	10
2	15	15	10
3	10	20	10

After 20 minutes from the start of mixing, the slurry has to be placed in the oven for optimal result.

Step heating

	Room °C	Tijd (min)
Step	290 °C (3°C/min)	90
Holding	60 mins	60
Step	550 °C (3°C/min)	87
Holding	60 mins	60
Step	700 °C (3°C/min)	50
Holding	60 mins	60
		407 (~7h)

Test planning

All materials, except for the oven, have to be ready at the start of the experiment.
Start in the afternoon (13:00), so the casts can be placed in the over overnight.

Start preparing the plaster slurry.
Mix the powder in a closed off bottle or cup.
Vacuum the plaster slurry after adding distilled water.
Cast the slurry
Leave the slurry to dry (3h)

Clean and store all materials

Wait 2.5 hours, cut away the mould.

Start preparing the phosphate bonded slurry.
Mix the powder in a closed off bottle or cup.
Vacuum the plaster slurry after adding distilled water.
Cast the slurry (4 min working time).
Wait till 20 minutes after mixing.
Cut away the mould.

Place all in oven

Results

Test 1:

Plaster (g)	Water(g)	Release agent
9	3	N

Quick first test to see if the plaster bonds to the 3D print material. Plaster : distilled water ratio was 3:1, mixed by hand, not put in a vacuum chamber. The mould had several days to harden out, but was not sintered.
Upon first judgement it seemed like it did, since the print could not be removed from the hardened plaster. Contrary to the initial assumption, the print could also be locked in place due to a tight form fit. Therefore, the mould had to be broken, so the print could be removed. After inspection with a microscope, it could be seen that the plaster had not bonded to the print cause there was no plaster residue attached to it.
The shape looks like a good replica of the end of the 3D print. However, no real measurements had been taken. Something that stood out were the two air pockets that had formed in the corners of the rectangular shaped pillar, before it turns into half a cylinder. It was no surprise, since the mixture did not go into a vacuum chamber.

Test 2:

Plaster (g)	Water(g)	Release agent
9	3	N

Test setup 2 was an exact copy of test one, this time with the cast shape positioned in the right way (horizontal). The 3D print was still stuck, upon removal the casted mould broke.

Test 3:

Plaster (g)	Water(g)	Release agent
9	3	Y

Usage of a release agent & vacuum chambre up to 0.6 bar.
The casted shape was copied nicely and could be removed in a semi okay way. Residue stuck to the rectangular cut-out for the metal pin and at the rectangular cut-out horizontally in the middle (probably because of the bold hole.
Main issue in this test are the air bubbles. Slurry has gone in the vacuum chambre, but probably needs to go in a more powerful one. Besides the little air bubbles all over the cast, 3 big air pockets have formed at the dome shaped top and at the corners of the horizontal rectangular cut out. Other than that, it seemed like underneath the square corners the density of the cast was lower



Test 4:

Plaster (g)	Quartz (g)	Water(g)	Release agent
6.75	2.25	4.5	Y

Usage of a release agent, 0.75:0.25 quartz:plaster ratio, 0.33:0.67 water:plaster ratio.
The 75% silica powder is based on literature. In this literature, The mould was very brittle. Upon removal of the cast shape, the whole top layer was torn out. It is assumed that this was caused by the high water concentration.

Test 5

Plaster (g)	Water(g)	Release agent
9	3	Y

(Test 3 +) Usage of a more powerful vacuum chambre (0.2 bar). Still a lot of bubbles.

Test 6:

Plaster (g)	Quartz (g)	Water(g)	Release agent
6.75	2.25	3.5	Y

(Test 4+) Usage of a more powerful vacuum chambre & less water. Broke upon removal

Notes

Possible improvements:

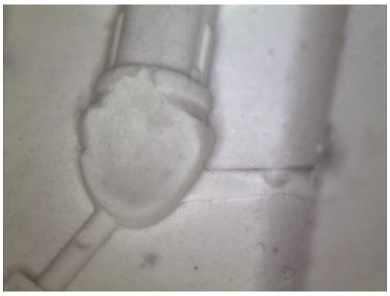
- Removal of the cast shape
- An appropriate (plaster specific) release agent
- Mixing
- Drying time
- Keep in mind that the casts also need to be sintered
- Up until now, the 3D print is pushed into the slurry and then a vacuum is created. It is presumed that the bubbles get trapped underneath the cast shape.

Test 7,8,9

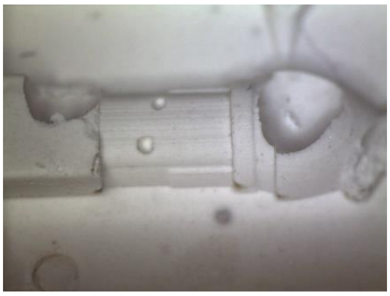
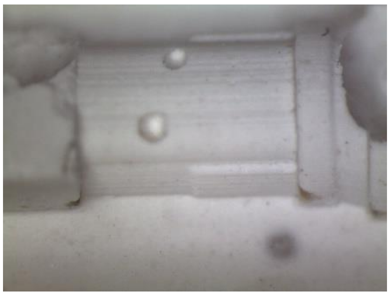
	Plaster (g)	Quartz (g)	Water(g)	Release agent
7	9	-	3	Y
8	6	3	3	Y
9	4,5	4,5	3.5	Y

From here on, the slurry is vacuumed twice with some stirring in between before the casted shape is put in. After the shape is in place, a third vacuum is created. This removed many of the bubbles, but did not get rid of the air pockets that get trapped at the top of the dome shape.
The goal, besides getting rid of the bubbles, is also to see the influence of added quartz powder. After the test two things became clear; adding quartz copies the original shape more accurately but also increases the brittleness of the casted part (before sintering).

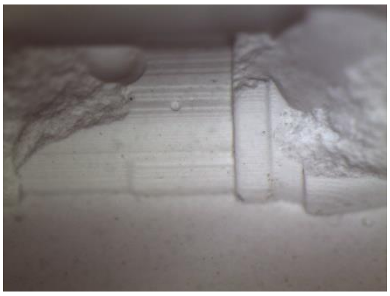
Test 7

Test 8

Test 9

Test 10, 11, 12

Plaster (g)	Quartz (g)	Water(g)	Release agent
4,5	4,5	2.75	N
4,5	4,5	3.0	N
4,5	4,5	3.25	N

Goal of this test is to see the effect of the concentration of water on the brittleness of the casted part and if the usage of release agent is actually required. It is not expected to have a definitive result on the influence of water on the brittleness. This will be tested by scraping with a pair of sharp pliers over the surface of the dried casts. The result won’t be expressed in exact numbers, but whether a noticeable difference can be observed.
The lowest water concentration was the least brittle and captured the highest detail. Furthermore, not using release agent has a negative impact on the release of the print. Although it is a release agent for silicone, it will be used from this point on.

Test 13

Plaster (g)	Quartz (g)	Water(g)	Release agent
4	2	2	N

New mould shape that might make removal of the cast easier.
No it doesn't. To brittle, screws go straight through.

Test 14

Plaster (g)	Quartz (g)	Water(g)	Release agent
1.8	7.2	Too much	Y

Release agent does help.
As done in the literature research, a 0.8/0.2 quartz/plaster ratio has been tried. Mixing is very difficult. As little water as possible was the aim of the test, though due to an error too much water has been used. This could also be seen in the quality of the cast; layers were barely visible.

Test 15

Plaster (g)	Quartz (g)	Water(g)	Release agent
4.5	4.5	2.8	Y

New plastic casting shapes were tried that are easier to remove due to their drafted walls. Also, the inserts were removed since it didn't add much to the tests. First try failed because the whole embossed shape stuck to the 3D print.

Attempt 2: Same problem

Test 16

Plaster (g)	Quartz (g)	Water(g)	Release agent
9	9	23.2	Y

Cavity broke off.

Test 17

Plaster (g)	Quartz (g)	Water(g)	Release agent
4.5	4.5	2.8	Y

(3x) In order to test good removal, the time between casting and removal have been varied. The prints are removed after 2h, 1.5h and 45 minutes. Easiest to remove was 1.5h and barely any residue was in the print. It seemed that the accuracy was a less good the earlier the print was removed.

Notes

Making the mould as accurate as test 10 seems difficult, although the amounts of plaster, quartz and water are the same. Possible difference could be:

- Cups now used are cut open for removal of the cast. This could have an impact on the compression of the slurry.
- The amount of release agent might interfere with the slurries ability to copy the details of the 3D print.

- Removing the bubble in the cavity of the mould might result in a more difficult removal of the 3D print (because it creates a vacuum).
- The drying time might influence the easiness of the removal of the mould but also on the accuracy. (Early removal leads to less visible layers?)

Test 18 (from the top)

Plaster (g)	Quartz (g)	Water(g)	Release agent
9	9	6	Y

Mould upside down. This way the vacuum chambre should be able to do a better job. Switched back to the original casting shapes, since the new ones with the chamfered walls don't work.
Vacuum: 1x to 100 bar.
Cast was in good shape again. Less air bubbles and easy removal.

Test 19

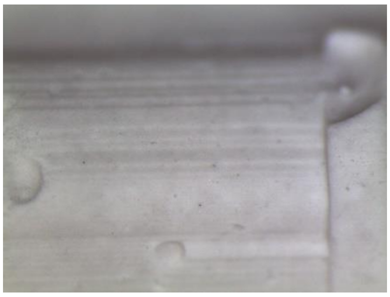
Plaster (g)	Quartz (g)	Water(g)	Release agent
3.6	5.4	3	Y

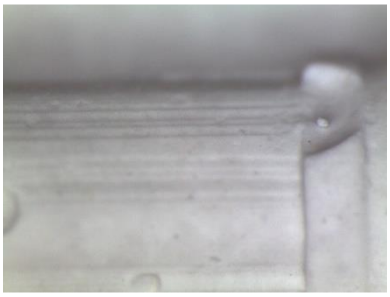
Also back to the original shape. Attempt to optimise the casting and prepare for the oven.
Cast was in a good shape again. Layers were slightly visible.
Vacuum: 2x to 100 bar.

Test 20, 21, 22 (from the top)

	Plaster (g)	Quartz (g)	Water(g)	Release agent
20 (150 bar)	6	6	3,79 (24%)	Y
21 (100 bar)	6	6	3,58 (23%)	Y
22 (100 bar)	6	6	3.48 (22.5%)	Y

Vacuum: 1x.
Back to the quality of week 10. Decreased air bubbles. Pouring from the top makes removing the 3d print and removing the cast from the cup easier and leaves a better result. 23% water gave a great result.





Notes

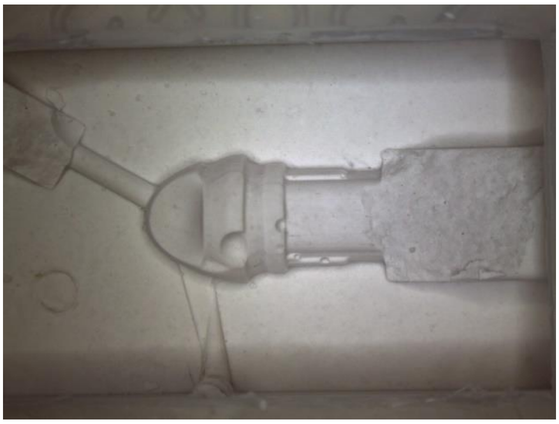
- Shaking/vibrating the slurry seems to make all solid parts (quartz, plaster?) sink to the bottom and make the liquids come up. This could also be a way to increase the accuracy of the cast.

- Water molecules have a size. A theory is that the less water is added, the higher the accuracy. In literature, it is stated that there is a correlation between the surface roughness and the water concentration.

Test 23

Plaster (g)	Quartz (g)	Water(g)	Release agent
3.6	5.4	3	Y

Test 21, difference is experimenting with vibrating the cast cup by hand when the slurry is in before going into the vacuum chambre. In previous tests it was seen that after shaking the cup liquid would come up to the surface. The sample has been manually vibrated (flicking the finger against the cup) and did not have a vacuum treatment.
The amount of bubbles is remarkably low, this is worth pursuing. Air pockets are still very present.

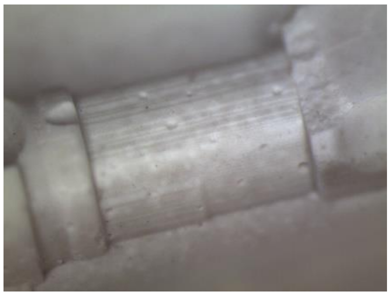


Test 24

Plaster (g)	Quartz 3um (g)	Water(g)	Release agent
3.6	5.4	3	Y

To see the influence of the grain size on the accuracy of the cast, this sample is made with quartz particles with a D_{50} of 3 um. The powder had not been mixed well enough.





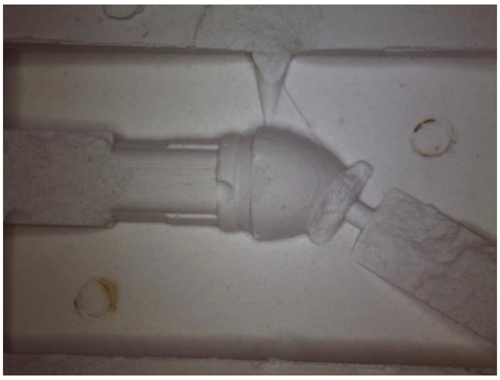
Test 25 - 30

Plaster (g)	Quartz (g)	Water(g)	Release agent	Bubble
6	6	3.58	Y	Vacuum
6	6	3.58	Y	Vacuum
5.4	3.6		Y	Vacuum
5.4	3.6		Y	Vacuum
6	6	3.58	Y	Vib & Vac

6	6	3.58	Y	Vib & vac

Test 33 & 34

50/50 quartz/plaster
5 um quartz (sample 33)
3 um quartz (sample 34), hoogste detail, geen uitsluitsel.

  sample 33

Test 35

Overdruk 4 bar, trillen, 50/50
Goed! Heel weinig bubbels

Test 36

0.75/0.25 quartz/plaster
12g investment, 4,21g water
Vibration by hand
Overdruk 4 bar

Test 37

8.4/3.7 quartz plaster
4.3 water
Vibration + pressure

Test 1 - oven

Plaster (g)	Quartz (g)	Water(g)	Release agent
2.7	6.3	3	Y
3.6	5.4	3	Y
4.5	4.5	3	Y
5.4	3.6	3	Y
4.5	4.5	2.69	Y
3.6	5.4	2.69	Y

All samples survived the oven. Less water resulted in a more brittle cast. No new insights regarding the level of detail.

Metal Cast 1

	Plaster (g)	Quartz (g)	Water(g)
0	60	60	36 $^{23.1\%}$
1	55	55	33 $^{23.1\%}$
2	60	60 $^{3\ um}$	36.5 $^{23.3\%}$

3um is the smoothest. No significant difference in shape replication.

Ceramic press 1

	Plaster (g)	Quartz (g)	Water(g)
0	90	90	36 $^{23.1\%}$
1	90	90	33 $^{23.1\%}$
2	90	90 $^{3\ um}$	36.5 $^{23.3\%}$
3	90	90 $^{3\ um}$	36.5 $^{23.3\%}$

Failed, too brittle

Conclusion

- 50/50 quartz plaster works for the oven and metal casting. Higher quartz concentration might result in a higher detail on the metal cast (not tested) since it results in a higher detail in the investment.
- Around 23% water seems to be the optimal balance for high detail/castability
- 3 um quartz results in a smoother finish on the metal