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Bachelor Thesis

Lost Print Moulding

Author:	Markus Dürbaum
DNI:	pl1x09fvyc
Supervisor:	Prof. Santiago Ferrándiz Bou
Advisor:	Prof. Rafael Antonio Balart Gimeno
Advisor:	Dr.-Ing Dragos Balan
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Abstract

This bachelor thesis is about the feasibility check and optimization of a new rapid prototyping technique "Lost-Print Casting" to cast light metals in more complicated forms. Partly it is like the existing Lost-Wax Casting, but instead of using wax or plastics that must be burned out at high temperatures, it uses a soluble material to 3D-print the positive.

The biggest advantage is that no oven or fireplace is necessary for the removing of the core. The process of burning out the material represents, when done with a simple and cheap fireplace, the highest rate of failure by introducing thermal cracks because of non-uniformly heating. For a uniformly heating, a relatively expensive oven for high temperatures would be necessary. Another advantage especially becomes relevant with high complexity. During the burn out process the material either flows out by gravity or burns up, it is possible that leftovers remain in the mould, affecting the quality and dimensions of the casted part.

The lost-print-casting doesn't need a special oven nor risking thermal cracks during the removal. It only needs to be flushed out with the solver liquid.

The potential target audience is the DIY-workshop and small companies with FDM 3D-printer, because except the unavoidable melting of the light metals, it only requires few money and relatively much work time. For middle and big companies, the process of producing complex shapes out of metal is dominated by metal-3D-printing and Lost-Wax Casting with specialised material, because they indeed require very expensive machines, but are requiring less machining and working time.

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1. Introduction

The production of parts out of metal often requires big and expensive machines. While parts with a very simple contour on only two axes can be machined with 2D-milling machines, parts with higher complexity have much higher requirements to the machine. Furthermore, some geometries cannot be manufactured at all with CNC-milling machines, for example if there are complex undercuts. For those parts, new process technologies such as 3D-printing can be used. The now fastest possibility of producing such a high complex part is the 3D Metal Printing (SLM). But the printer for this application is very expensive and normally only available for big companies. One possibility to lower the costs is the Lost-Wax-Casting. This requires less charges, but more working time. This bachelor-thesis deals with an improvement of this concept by substituting the wax-model with a more common 3D-printing material to economize this part and to improve the reliability.

2. Task Specification and Objective

The task is to find a suitable alternative to the printing and melting of wax-models. The expensive part with this part is, that a special printer and a special wax-filament is necessary. The replacement should be printable on the widely used 3D-printers with commonly available filament to lower the costs. The process of burning out the wax should be replaced with a method that doesn't need a higher temperature oven and prevents the mould from getting thermal cracks while removing the positive model.

The acquired solution should fulfil all requirements. It should be easy to process with a low money investment and a quality of the casted part at least comparable with the Lost-Wax Casting, maybe even better and with a higher success rate.

4. Way of Proceeding

To start with the project, an investigation of the current processes and materials available is essential. Suitable materials and processes must be examined and compared to each other.

The practical part starts by ordering the selected materials in a low amount for test purposes. A test-part has to be created that can investigate different quality characteristics. This is being printed with the 3D-priting filaments, and with every combination with the different casting materials a mould is being produced. After the dissolving, drying and casting of aluminium the results must be analysed and compared. The most suitable process is being examined and is, if possible, improved.

5. Investigations

To enhance the process, the existing process of Lost-Wax-Casting and existing materials must be investigated. An analysis of the producing of the wax-part and the dissolving can help to improve the planned new process. Additional, the third part of the process, the pouring of molten metal into the cast, will be almost completely taken over to the new variation because the changes don't affect this part. By investigating the casting, important information and requirements for the selection of the materials can be obtained.

5.1 Lost-Wax-Casting

Figure 1: Bronze sceptre from the Nahal Mishmar Hoard [1]

The first parts produced with Lost-Wax-Casting are from approximately 3700 BC in the Middle East.

Until the application of 3D-printers there were only two variations: If a completely new model must be produced, the figure is being modelled out of wax by hand. After finishing this, channels for the insertion and extraction of metal and air are added. To obtain the cast, the investment material is applicated in a big form or in thick layers ('stuccoing'). After the solidification, the wax can be extracted. To do so, the object is heated up and turned upside down to allow the wax to flow out. Into the hollow mould, the molten metal is poured. If small amounts of wax are still in the mould, they burn up by the high temperatures, which can, depending on the position and form, affect the cast part negatively by introducing gas bubbles. After the metal is cooled down, the mould is being destroyed to reveal the produced part. Depending on process parameters and the combination of the casting material and poured metal, the surface can vary from fine detailed to brimmed over with bubbles, which makes a postprocessing obligatory.

The second traditional method ads a step before these processes. To copy an object, first a negative-form is being produced around the original, in which the wax is being filled in. For complex forms, this can be done with smaller parts that are set together.

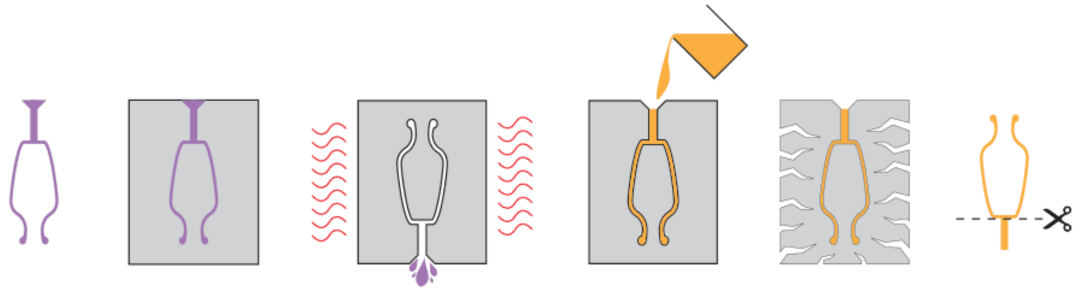

Figure 2: Process of the Lost-Wax-Casting [2]

Since modern fabrication techniques exist, there are also more possibilities to create the wax-model. Especially noticeable are the 3D-printing technologies. With suitable printers and a suitable wax, nearly any complex form can be printed and processed easily, with high accuracy and a high reproductivity. But make the wax printable, additives must be added, which results in problems during the extraction of the wax. While a high amount of the wax can flow out, there are many remains in the mould that can't flow out and require high temperatures to burn them out. This stresses the mould additional.

Nowadays, the Lost-Wax-Casting is nearly only found in the prototyping process with complex parts. Two examples for the few applications in quantity is the Rolls-Royce-Figure 'Spirit of Ecstasy' which is still sculpted in hand-cast using the lost-wax process and the creation of dental protheses.

Figure 3: Rolls-Royce 'Spirit of Ecstasy' [3]

5.2 Materials

The materials that are used are varying a lot, depending on the field of application and requirements. As casting material nearly all metals can be used, but especially metals with a low melting point are suitable. The metal point must be lower than the maximum service temperature of the investment material. The materials that are used often in this process are aluminium and bronze for technical applications, copper, brass, silver and gold for jewellery and medical applications.

The used investment materials for metals are gypsum-bonded, phosphate-bonded (ammonium phosphate), silicate-bonded and acetate-bonded:

Gypsum-bonded investment material: [4]

The plaster consists of calcium sulphate dihydrate and water as binder and two high temperature modifications of quartz, especially tridymite and cristobalite. It can have additives that are raising the thermal expansion or lowers or raises the curing time.

It is only suitable until a preheat temperature of 700°C, because the gypsum disintegrates at temperatures over 750°C and builds metal sulphides that harm the metal alloy. With this low temperature, normally only very small parts out of a gold alloy with a low melting point are processed to not exceed the maximum temperature.

Phosphate-bonded investment material: [5]

For this material, the cristobalite and tridymite is being bonded by magnesium oxide and ammonium sulphate and mixed with water and silica sol. It expands during the curing, but the amount can be controlled by the ratio of the components. The curing requires three steps, including preheating in an oven at 160°C and at 250°C. The emerging toxic ammonia must be exhausted into open air. It decomposes at temperatures over 1300°C.

Silicate-bonded investment material: [5]

Silicate-bonded investment materials consists of quartz, tridymite and a liquid out of tetraethylorthosilicate, which reacts with water to silicic acid and ethanol.

It is suitable until a preheat temperature of 1100°C and doesn't expand during the curing, but the curing requires an oven at 180°C. A typical application is the model casting in dental technology.

Acetate-bonded investment material: [6]

This investment material is specialized for the application for titanium. It has esters of acetic acid for the acetate-bound. A big advantage is the fine-tuning of the expansion during the curing. It can be controlled in both directions by varying the curing temperature around the standard 965°C and the curing time around the standard 30 minutes. For the casting, a preheat temperature of 430°C is sufficient and guarantees a good surface and a good shape accuracy with the 1668°C hot titanium.

Speed investment material: [7]

These materials are also called 'Shock-Heat-mass' and are binding much quicker than the mentioned materials before. It can be processed in an oven 15 minutes after mixing and the preheating process only lasts 90 minutes instead of the conventionally three to four hours. The binders are magnesium oxide and ammonium dihydrogen phosphate, the fillers are quartz and cristobalite. As with the phosphate-bounded investment material, it is mixed with aqueous silica sol.

Printing material:

Wax: [8]

The material is a wax-like filament. Theoretically it can be printed with every FDM-printer, although because of the softer texture many printers have problems with this filament. With a nozzle temperature of 180°C and a low printing speed the model can be printed. Most of the wax can be melted and poured out, while the rest of the wax must be burned out with relatively high temperatures. The possibilities of processing the model are considered as good and a relatively thick shell is recommended to maintain the shape and compensate the poor mechanical properties. It costs 59,90€ per 0,75kg at the German online shop 'filamentworld'.

PLA/ABS: [9]

These materials are the standard materials for 3D-printing and widely available. They are printed at 210°C with a high printing speed. These materials don't flow out easily at high temperatures and material must be burned out at high temperatures. PLA costs 34,90€/kg at the same store.

PVA: [10]

PVA is mostly used as support material in dual printers. It has a good water solubility with no remains and no toxic products. The printing quality is considered as high and can be good postprocessed. PVA costs 34,90€ per 0,3 kg.

HIPS: [11]

This material is similar in the application and processing to PVA. It is also used as support material because of its solubility in lime extract. It costs 34,90€ per 0,75kg.

6. Requirements

The requirements for the casting material are mainly dominated by the applied process. Because of the water as a main ingredient in all considered materials, the side effect of the water on the printed material must be reduced. That can be achieved by a lower amount of needed water, a shorter curing time and a higher viscosity. Further, the surface of the moulding material should be as smooth as possible to achieve a better surface structure of the casted part and lower postprocessing as well. To simplify the process for the home application, the moulding should be possible without costly equipment and without toxic materials.

The selection of the printing material is dominated by the possibility of dissolving and, of course, the price. The solving fluid should be easily gainable, nontoxic and easy to dispose. Further it should not react with the moulding material to prevent side effects. Of course, it should be easily printed with common 3D-printers and reachable in common 3D-supply-stores.

7. Material Selection

The considered materials are analysed with the requirements shown before. The phosphate-bonded and the speed investment material are not suitable for home applications because of the emerging toxic gasses during the curing and because of the need of an extra oven. The Acetate-bonded investment materials are not suitable for home applications because of the need of a high temperature oven that can be controlled accurately.

Of the remaining two materials, the gypsum-bonded investment materials are suitable for home applications without problems because it is not emerging toxic gasses and can be processed in a common household, even without the use of an oven. The silicate-bonded investment material needs an oven at a temperature of 180 °C, but most material combinations of the gel-sol process don't emerge toxic gasses, so it could be done either in a normal oven with simple modifications or, if a separation is desired, in an additional cheap and small oven.

The material selection for this project and the practical execution is limited by the material costs and the use for other projects. Because the silicate-bonded investment material is a very specific material and would be probably only used for this project and not for later projects, it is too expensive to buy a bag of many kilograms from which only approximately 300 grams would be used for this project. So a gypsum-bonded material is used for the practical execution. This material can be also used for other projects because of the universal properties and is very cheap. To reduce the curing time, and with that the side effects on the part, a quicker drying variant is used. It is from the company 'Big Mat Iberia' and is named 'Yeso Manual Rápido Construcción' and costs approximately 0,12€ per kg.

Figure 4: Used gypsum-bonded investment material

For the printing materials, the classic materials like PLA and ABS are not suitable because they have to be burned out of the mould, which would be like the common lost-wax casting and requires a high temperature oven.

HIPS needs lime extract, which is a little difficult to get and not very easy to handle in home applications. Furthermore, the lime extract also contains water that would have side effects on the mould like the pure water for PVA

The selected material for this project is PVA. It is soluble in water, which is easily reachable in every household and easy to handle. Other arguments are the higher accessibility because it is commonly used in 3D-printing as a support material and the good printing properties. A disadvantage is that the water in the gypsum-bonded investment material can have a negative effect on the PVA during the curing and the possible side effects of the water as the solvent fluid on the cured gypsum-mould. But because these effects would happen with all material combination, this disadvantage is accepted and examined during the practical execution.

8. Testing Model

The testing Model should contain shapes that are not normally used for castings to also show the weaknesses and the limits of the process. To reduce the practical work, a relatively small part is being designed with the dimensions of 60mm x 30mm x 52mm. As shown on the following pictures, it consists of a flat ground plate and two towers. The ground plate has a thickness of only 2mm to simulate small bridges of parts and to see if that's possible to process. While the volume between the towers is expected to go well, the flat areas around them and especially the four corners will probably show weaknesses of the process because of the bad water and metal flow in these areas. The two towers have parallel surfaces on the inside to recognize a deformation and have different shapes to see the effects on the geometries. Both structures are getting thinner at the top to see possibly occurring effects.

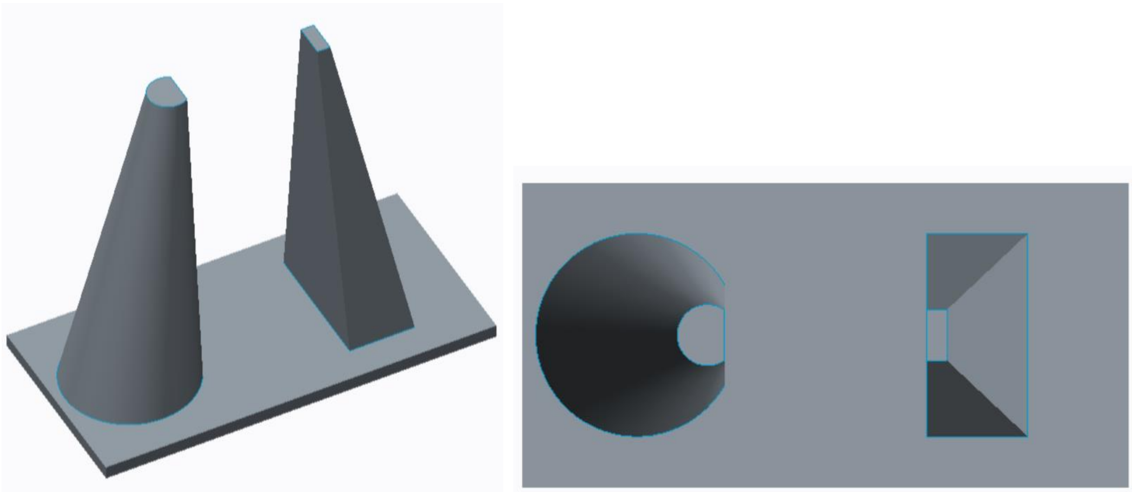

Figure 5: 3D-model of the test-part

9. Processing

With the selected materials and the designed test-part a first iteration of the process can be performed. Because of the availability of only one material per group (gypsum and PVA) and the limited time also only one iteration is being run.

The part is printed by Santiago Ferrándiz Bou, the other practical works are realised with the help of Miguel Angel Peydro Rasero.

All steps done are shown in the following:

9.1 3D-Printing

The 3D-printing is done with a common FDM 3D-printer of the university under the command of Santiago Ferrándiz Bou. It is printed with 20% infill and a rough layerheight of 0,3mm. In the following two pictures, a simulated model of the printing process and the actual printing is being shown.

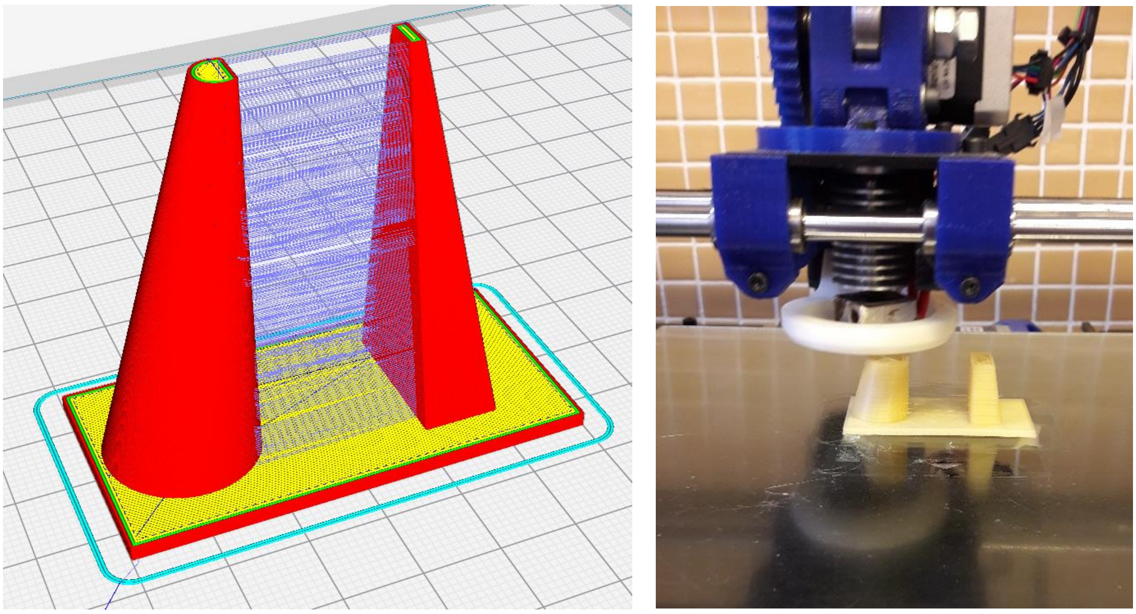

Figure 6: Simulation and printing of the test-part

The printed model turned out good, only with a few stringing effects where the printin nozzle skipped from one tower to the other. But these are so fine that they simply disintegrate quickly during the moulding and totally don't disturb the part in any way. As visible in the following pictures, the 20% infill gives the part a good stability and resistance to deformation while it saves material and reduces the time of dissolving.

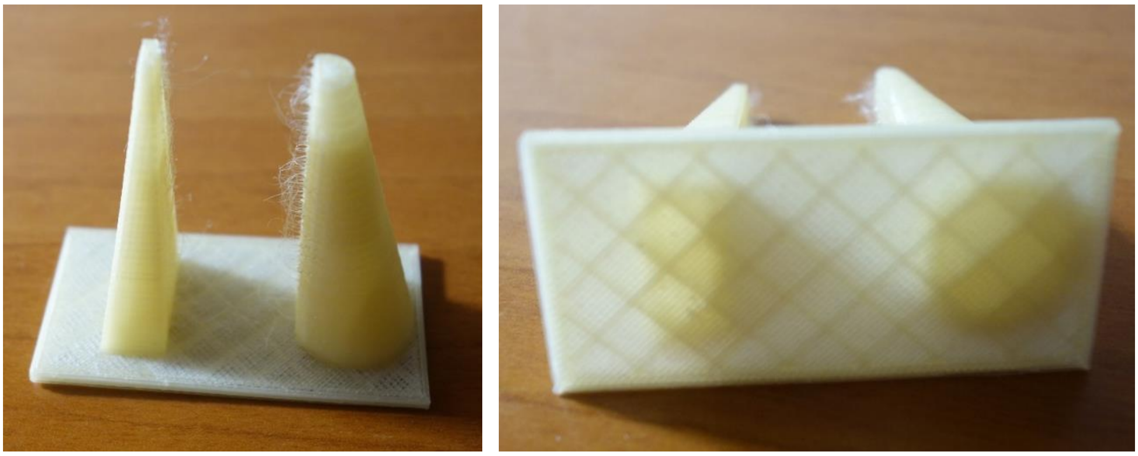

Figure 7: Printed test-part

The structure of the layers and the top layer is shown in the following two enlarged pictures. Where the nozzle skipped to another layer or position, a bright mark is visible that interrupts the continuous pattern. But this effect is only visible in a high enlargement and has probably only a small effect on the outcoming result. In the enlargement of the top layer the small gaps between the strings is clearly visible. For the dissolving of the PVA this structure is positive because of the higher surface area that has contact with the water.

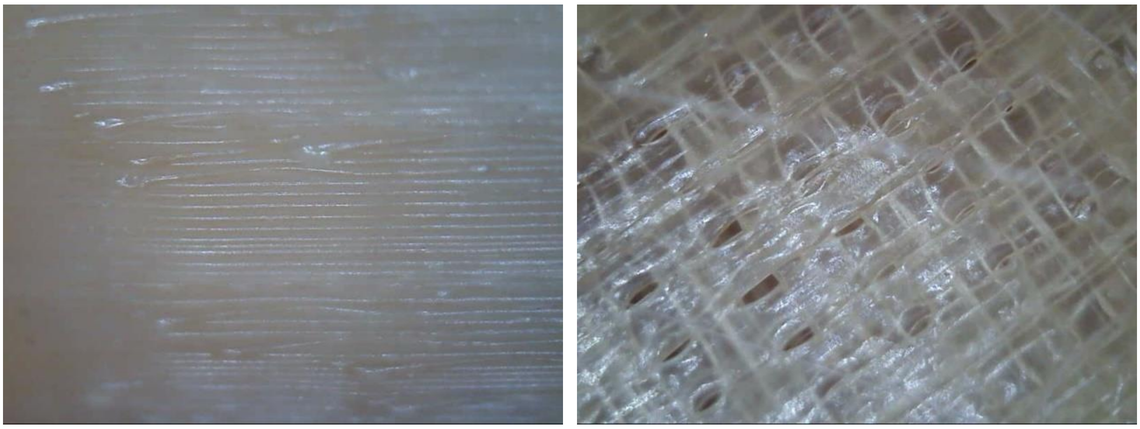

Figure 8: Enlargements of the printed structure

With different printing parameters the structures and properties can be controlled and changed if necessary.

9.2 Moulding

For the moulding, the dimensions of the mould have to be examined. To simplify it, a simple rectangle is being formed with bented metal sheets that are fixed with clamps. To achieve a good mould, the minimum wall thickness from the part to the metal sheets is chosen with 20mm. This results in mould dimensions of 100mm x 75mm x 80mm and a total volume of 600cm³.

Figure 9: Arranging the mould

To hang the printed part from above in the gypsum, a thin metal stripe is cut in a accurate length. For the apertures to enable the fluid- and gasflow, two small metal parts are cut out and glued onto the printed part and the metal sheet.

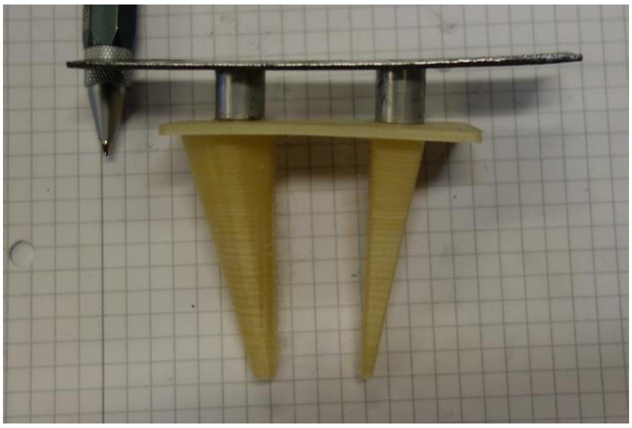

Figure 10: Glued test-part with metal

Figure 11: Mixing and pouring of the gypsum

The gypsum is being mixed with water until it has the commonly recommended consistency and texture and has no visible air bubbles. It is then poured into the prepared mould without the PVA-part. After the mould is filled, the part can be inserted. This is done with small movement and shaking of the part to ensure a good surface covering without introducing gas bubbles that would lead to a poor surface and more postprocessing. After this step, the mould is put in an oven at 80°C to shorten the curing time. For the home application, this is not necessary. Without an oven the curing time would simply be longer until the next process step can be started.

Figure 12: Insertion of the test-part and curing

9.3 Draining

After the curing of the gypsum, the clamps, metal sheets and the three metal parts can be removed.

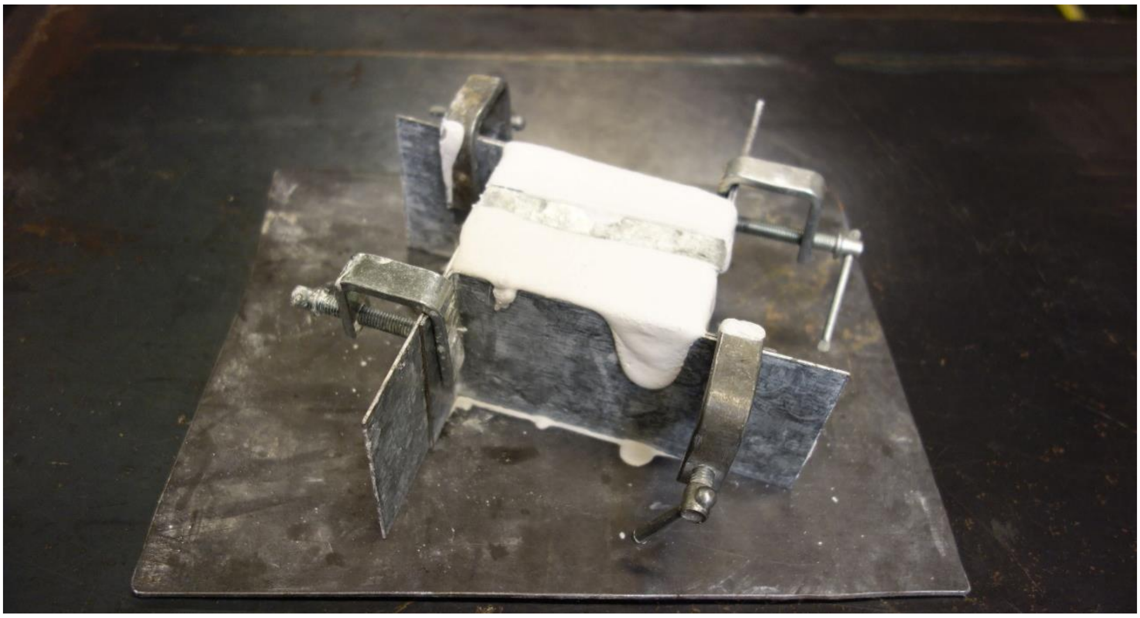

Figure 13: Cured mould out of the oven

The now visible PVA material is very soft and behaves like a gel when touching because of the contact with the water in the gypsum. Nevertheless, the visible areas are making a good first impression and have a good and detailed surface.

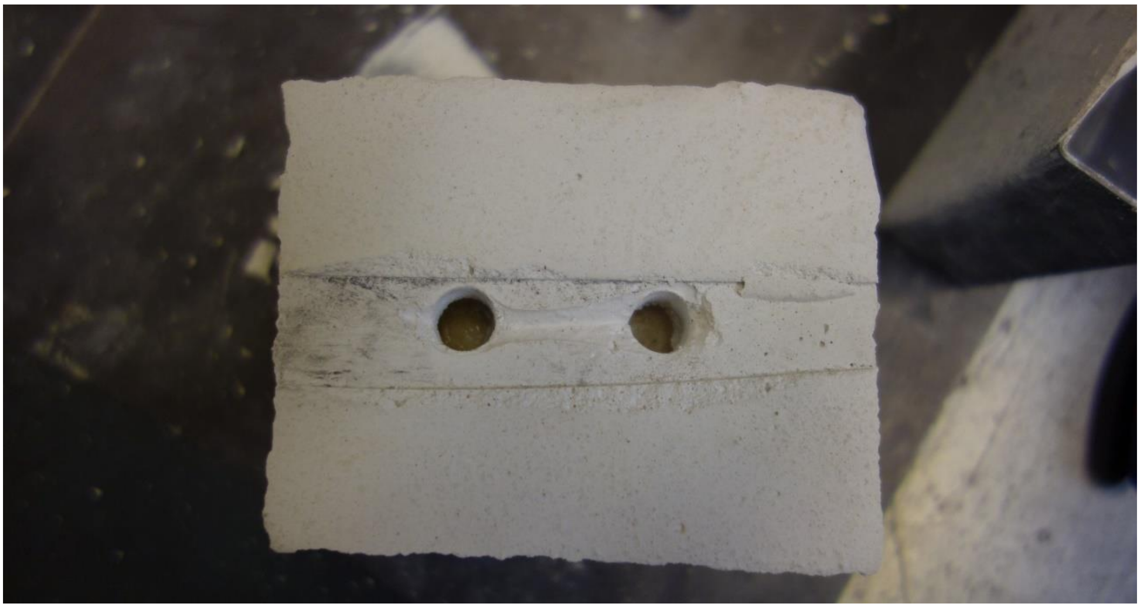

Figure 14: Mould without the helping structure

The draining of the PVA is done in a common kitchen sink. Water is poured in a constant low amount into one of the two holes to achieve a circulation of water in the mould. To accelerate the process, it is recommendable to induce every hour a stronger water pouring. During these seconds, also bigger part of PVA that separated themselves from the surface can be flushed out. It is also recommendable to poke around in the mould from time to time with a flexible tube or string to again accelerate the dissolving, although the two tips are additional and not general necessary. For this trial a total dissolving time of 10 hours is used.

Figure 15: Draining of the PVA

The results of the draining after drying for two days in the sun are shown in the four following pictures. The PVA seems to have been dissolved completely, although because of the complex geometry, for example the edges of the ground plate can't be examined without special cameras. Compared with the pictures from before the draining, it is visible that beneath the PVA also a small top layer of the fine gypsum is dissolved and more of the bigger particles are visible. But even with this effect, the remaining surface of the towers shows the layers of the printed part very good and is very detailed.

Figure 16: Surfaces of the dried mould

Figure 17: Surface in the mould at the round tower

9.4 Casting

For the casting material lead is used instead of aluminium for this trial. Aluminium is not used because of the limited application possibilities at the university and would need a longer preparation. Because lead has a much lower melting point the effects of burning out of remaining material and the vaporization of remaining water are lower, but still present in a average amount. Nonetheless the casting with lead instead of aluminium still shows good the process, weaknesses and strenght of that method. The lead is heated up ina a pan on a gas burner and then poured in the two holes until the mould is completely filled up.

Figure 18: Melting the lead

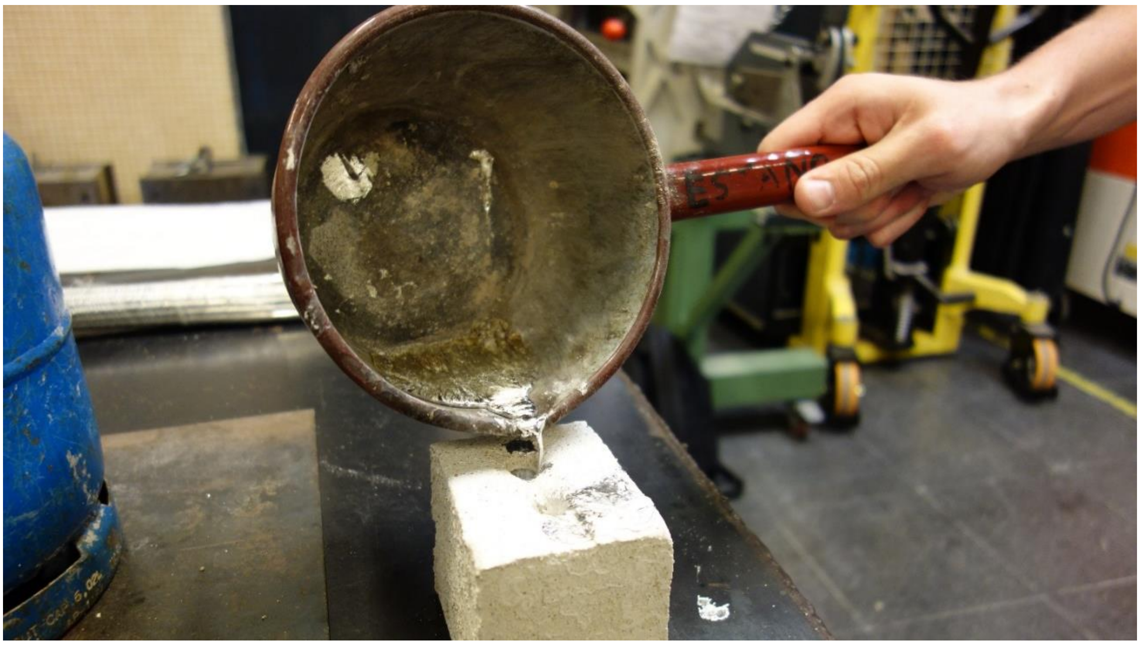

Figure 19: Pouring into the mould

During the casting a few gas bubbles from the water and remaining PVA occur and raise some material out of the mould, especially when the fluid level reached the ground plate. This is a clear sign that there is some more PVA unsighted in the edges and corners of the mould.

After the casting, the metal must cool down and solidify completely.

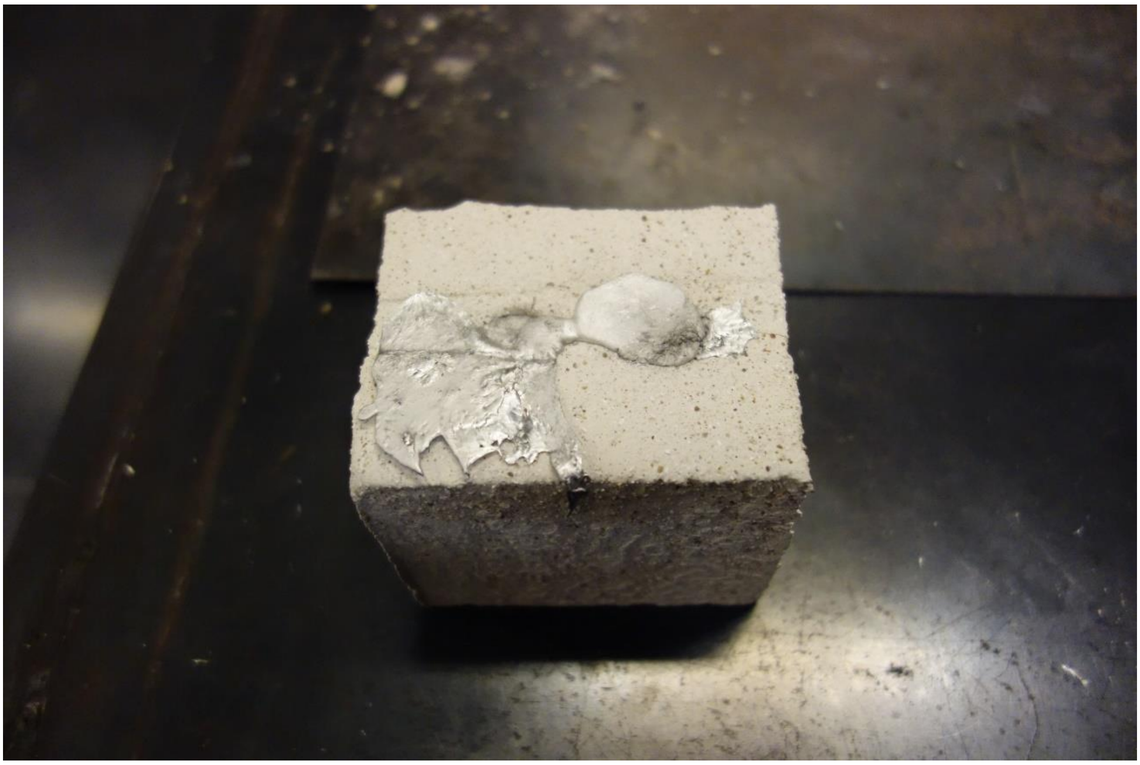

Figure 20: Mould after the casting

9.5 Postprocessing

Figure 21: Removing of the mould with a hammer

To remove the casted part, the mould has to be destroyed. This is done with pointed hits with a hammer and levering with a screwdriver without effecting or destroying the part. After a quick cleaning from expendable dust and fragments the also casted apertures are removed with a saw and the surface is being levelled with a file.

Figure 22: Removing of remainings with tools and a saw

10. Analysis

The results are shown on the upcoming pages. Beside the casted part, also parts of the mould are analized. This helps especially to understand what happened in the corners and edges of the ground plate and of the tips of the towers.

Looking at the part it is obviously that some areas are missing or in bad condition. Considering a volume of the model (measured in CAD) of 14,73cm³ and a density of plumb of 11,34g/cm³ the full part should have a weight of 167g. But the actual weight is only 144g, so 23g of material are missing from the part.

Figure 23: Casted part, frontview

Of the ground plate three edges are in bad condition with missing and mixed material, while the fourth is comparable good. The corner in the front is also in very bad condition. While in the middle and behind there is pure lead, near the front corner obviously some PVA and some gypsum remained, mixed partly with the lead and blocked it from flowing further *(figures 23 + 24)*. Another reason that especially the plate is not fully filled is reasoned in the execution of the casting. The mould lay on a table and wasn't moved or shacked during and shortly after the pouring of the metal, so enclosures where air and material couldn't escape were likely. That also explains why one side is more filled than the other and near the borders to the unfilled areas the big gas bubbles in the material *(figure 26)*. The bridge between the towers and in some other areas are also visible enclosures and gaps because of trapped air. *(Figures 23 – 26)*

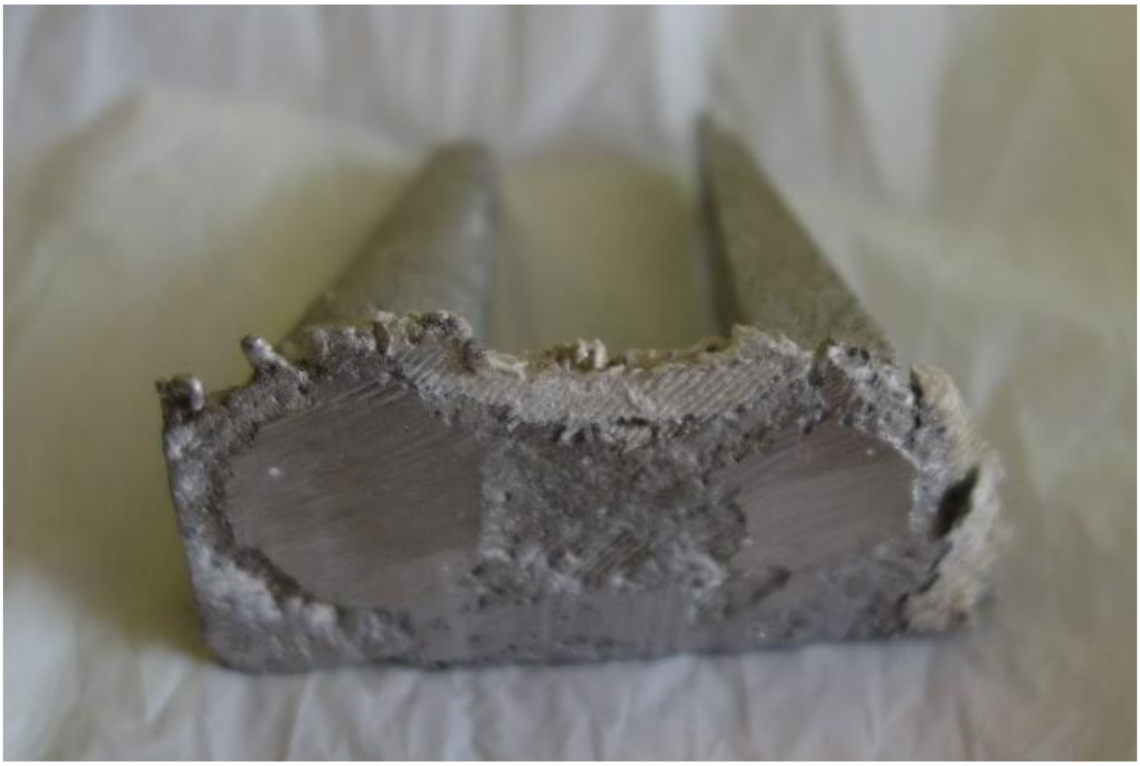

Figure 24: Casted part, bottom view

Figure 25: Casted part, bridge

Figure 26: Casted part, occurring holes

Figure 27: Mould, unsuccessful edge

The analysis of the areas of the mould where the ground plate used to be shows big differences between the edges. While in the 'good' edge the contour is clearly recognizable and no remainings can be found *(figure 28),* in all other three edges still exist material that looks like a mixture of mainly overheated PVA and traces of gypsum and lead. *(figure 27)*

That there are remainings of these materials, especially PVA, means that the water circulation in this area wasn't good and long enough to flush out everything and, as foreseen, the used geometry is inappropriate for a good fluid flow.

Figure 28: Mould, successful edge

Figure 29: Mould, partly assembled

Figure 30: Mould and casted part

The analysis of the two towers also shows weaknesses of the used material combination and the process. Because of the geometry, the fluid flow at the thicker and lower segments is much stronger than at the thinner segments. Furthermore, because the water is inserted through the groundplate, the thicker segments are much longer in direct contact with the water. Those two circumstances lead to a much rougher surface in the lower segments, while the thinner segments are representing the original shape of the printed part in detail with a very good surface *(figures 31 + 32)*.

The tops of the towers are another weak point considering the water flow. The circulation is very weak there and the bubbles *(figure 33)* indicate remaining PVA and water that burned up/vaporised during the casting and small particles of the gypsum that were not washed out. The mould *(figure 34)* also proves that these remainings had an important role in the forming of this error.

Positive to mention is that the shape and the dimensions of the part is almost identical to the original. For example are the towers parallel to each other and did noch bent in any direction.

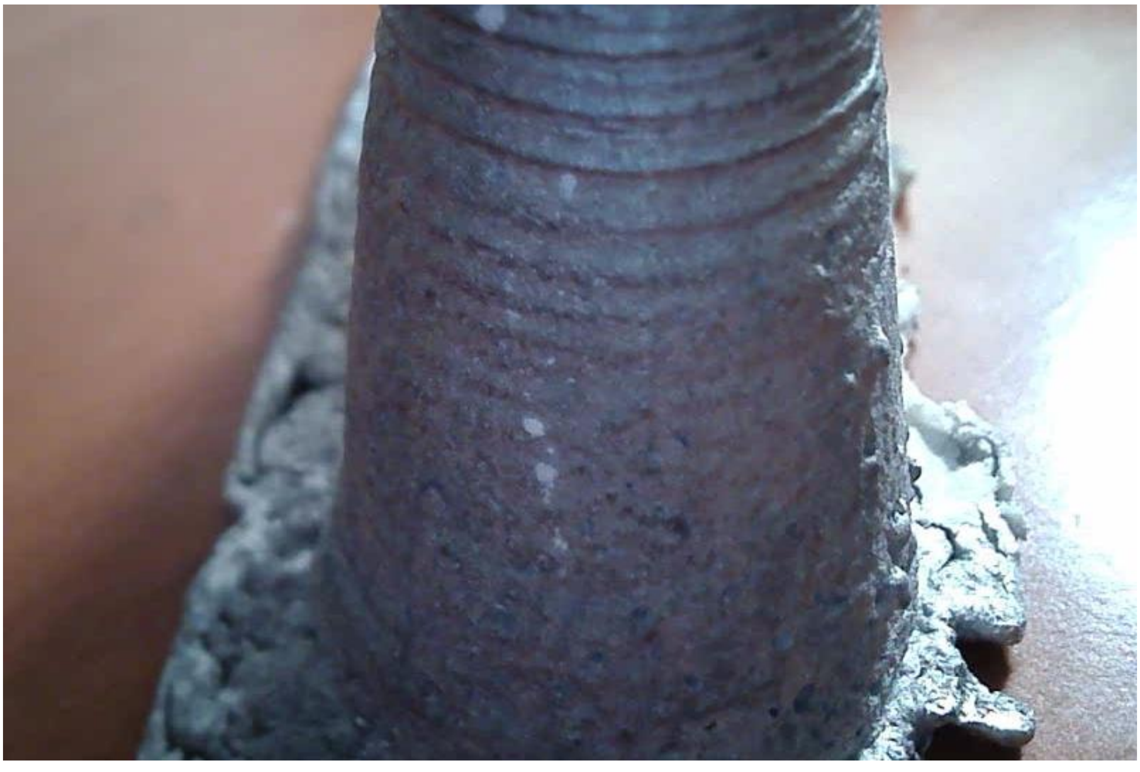

Figure 31: Low enlargement of the structure of the tower

Figure 32: High enlargement of the structure of the tower

Figure 33: Enlargement of the top of the tower

Figure 34: Mould of the top of the tower

11. Recommendations

1. The most obvious thing to do is to change the moulding material. As mentioned in the chapter 'Materials', the gypsum is the only material used for this project, while different materials like other variants of gypsum-bonded investment materials and silicate-bonded investment material are also possible for home applications. These can enhance the processability and can lower the negative side effects of the water on the mould.

2. To confirm that the used materials are suitable, this has to be proven by actually casting with more technical metals like aluminium and not lead. The higher temperatures can have a negative effect on the mould that has to be excluded for a real recommendation of the whole process.

3. Instead of PVA, other printing materials like HIPS can be tried out. Although these may not be very different to PVA and lime extract is a little more difficult to get, it may have a positive effect during the dissolving of the material.

4. Another recommendation, that is the most promising, is by using a resin that is not solvable in water and is being applied on the surface of the printed part before creating the mould and acts like a separation layer between the materials. This layer prevents the water that's in the investment material to have negative effects on the PVA and protects the solidified investment material from the circulating water during the dissolving of the PVA. After this step, the resin is dissolved with a low amount of the needed solvent. Beneath the advantage of preventing the mentioned side effects, it also makes a very good and detailed surface easily achievable.

12. Conclusions

The trial described in this bachelor thesis was done with very cheap materials that are not specialised for this purpose. Furthermore, just one material combination was realised without the possibility of enhancing the process like described in the chapter before. Additionally, the used geometry of the part was not very suitable for this process.

Despite of all these negative circumstances, the results were relatively good and show that the described process with some enhancements is totally suitable for home applications. Especially the applying of a resin as a temporarily barrier between the materials and as a surface improvement looks very promising and should be tested in further iterations.

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