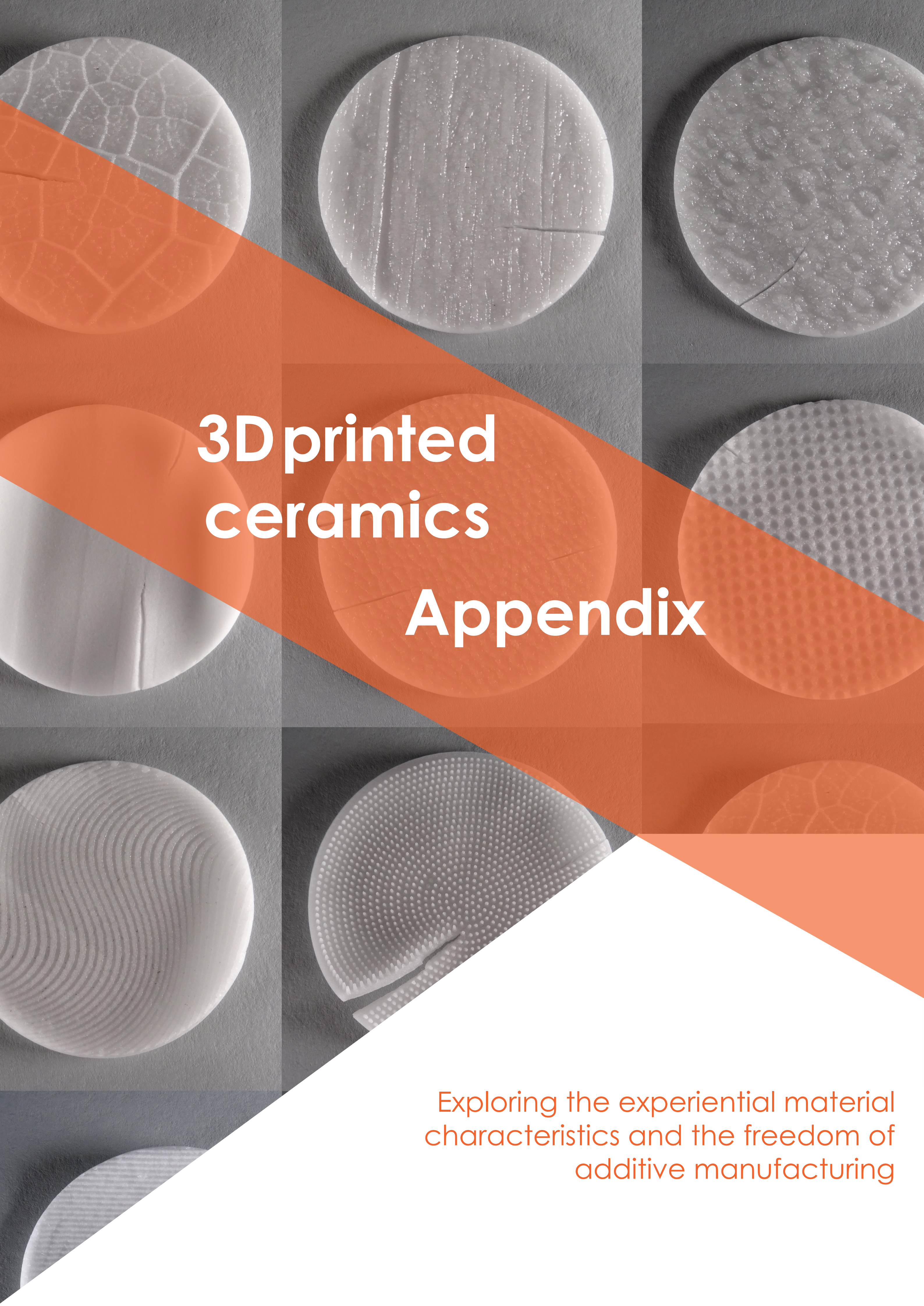


3D printed ceramics

Appendix

Exploring the experiential material characteristics and the freedom of additive manufacturing

Appendix A: Traditional ceramics

Composition

Ceramic is defined as “Any non-metallic solid which remains hard when heated” (Lexico, 2019). Because of this there is not one standard composition when it comes to ceramics. There are many types and to explain what types there are they will be split up into ceramics with clay and without clay.

With clay

These ceramics are made with materials from the earth. In most cases they are a mixture based on the naturally occurring material silica (SiO_2). It will include clay minerals like kaolinite ($Al_2[Si_2O_5][OH]_4$), silica sands and/or feldspars (Science Learning Hub, 2010).
The clay minerals are considered to be the formers since, mixed with water, they allow for unusual material deformation. This is why clay based ceramics allow for such diverse processing methods like slip casting and plastic forming (plasticity: flexibility of the clay, influenced by clay’s particle size, water content, aging) (Mason, 2016).
Silica sands can be added to the clay body acting as a filler. Meaning they will provide more strength to the green (unfired clay body) shaped object and help to maintain the shape during firing (Mason, 2016).
Lastly feldspars can be added to the clay body. Feldspars act as fluxing agents. Meaning they will lower the melting point of the main glass forming minerals, usually silica and alumina (Mason, 2016). This results in controlled vitrification (transformation of a substance into a glass. Gives ceramics a, for fluids, impenetrable surface).

Without clay

Ceramics which do not actually contain clay are often so called technical, engineering or advanced ceramics. These can be oxides, non-oxides or combinations of the two (Science Learning Hub, 2010). In this chapter the composition of advanced ceramics, both oxides and non-oxides, is explained.

Oxides
Common oxides used are alumina (Al_2O_3), zirconia (ZrO_2), silica (SiO_2) and beryllia (BeO) (Peng, 2013). These non-clay oxides start as a powder with a certain purity, particle shape and size. They are often hard, angular shaped, brittle and gritty. Furthermore, the particles do not adhere well to one another when wet and do not adhere at all when dry. Because of these properties oxide powders are used as abrasives and, when in fine particle sizes, as polishing powder (Ruys, 2019).
These non-cohesive, gritty, hard and angular particles don’t show plasticity when made wet. Even when the particles are milled and sized down to submicron range they show much inferior plasticity compared to clay. This makes forming the raw material challenging to impossible and to solve this the oxide powders often are blended with synthetic chemicals like deflocculants, binders and plasticizers (Ruys, 2019).
Adding clay to the high-purity oxide powder, like is done for porcelain, is not possible since clay contains metal impurities which will deteriorate the properties of the advanced ceramic.
So, first a liquid solution is made containing the finely milled oxide powder (called slurry) and afterwards the chemicals are added (Ruys, 2019). What the purpose is of the deflocculants, binders and plasticizers is explained below (Ruys, 2019).

- Deflocculants are added to prevent the particles from forming a gel by creating robust interconnected networks. By optimally using deflocculants the slurry will become stable and contain the maximum amount of solid particles for the amount of liquid used.
- Binders are added to the slurry to increase green strength when the formed material is dry. Often an organic blend is used. So, because of the binder the green formed object will not collapse when dry.

- Plasticizers are used to increase plasticity and flexibility. Normally the wet slurry has no plasticity but when the plasticizer is added the slurry will develop a doughy and sticky consistency.

So, oxide advanced ceramics consist of a raw, non-clay based, oxide powder blended with deflocculants, binders and/or plasticizers, depending on the forming method, resulting in a liquid solution containing fine particles (a colloidal) (Ruys, 2019).

Non-oxides

Common non-oxides are carbides, borides, nitrides and silicides. For example boron carbide (B_4C), silicon carbide (SiC) and molybdenum disilicide ($MoSi_2$).

Composites

Composites are a mixture of oxides and non-oxides or oxide or non-oxide particles which are reinforced (Taylor, 2003).

Properties

Each type of ceramics has different specific properties but the main properties ceramics are known for are (The American Ceramic Society, 2018):

Differs per ceramic type

- Medium to extreme hardness
- Electrically insulating or electrically conducting
- Semi- transparent or opaque
- Low to medium thermal shock resistance
- Poor to high impact strength
- Low to high impenetrability
- Good wear resistance
- Low to medium machinability
- Low to high thermal conductivity

All ceramic types

- High elastic modulus
- High dimensional stability (The degree to which a material maintains its original dimensions when subjected to changes in temperature and humidity)
- High resistance to chemical attack
- High weather resistance
- High melting point
- High working temperature
- Low thermal expansion
- High compressive strength
- High resistance to corrosion
- Low ductility
- Low tensile strength

With clay

Clay based ceramics are classified as follows (Thulasi, 2018):

- Earthenware
- Stoneware
- Porcelain
- Bone china

The specific properties per classification are listed below.

Earthenware

- Medium hardness
- Opaque
- Thermal shock resistance
- Poor impact strength
- Low impenetrability
- Low thermal conductivity

This is a low fire ceramic type often based on low-refractory clays (Tite, 2008). It will be fired at a relatively low temperature of between 1000-1150°C. Firing at a low temperature means it is not fired to the point of vitrification leaving the surface slightly more porous and course. Because of this it is common to glaze earthenware products to overcome its porosity (Science Learning Hub, 2010). Not firing it to the point of vitrification also results in lower hardness and durability. Earthenware clay has high plasticity meaning that it is easy to form. Furthermore, it contains mineral impurities which are visible to the eye. Earthenware clay comes in many different colours. This is dependent on where in the world the clay is obtained (Peterson, 2019).

Stoneware
- High hardness
- Electrically insulating
- Opaque
- Thermal shock resistance
- Medium impact strength
- Medium impenetrability
- Low thermal conductivity

This type of ceramic exists in mid-fire and high-fire refractory clays (Tite, 2008). Meaning it will be fired at a temperature of between 1160-1225°C (mid-fire) or 1200-1300°C (high-fire) (Peterson, 2019). Since this clay type will be fired at a higher temperature it now will be fired to the point of vitrification. So, now the surface is left smooth and glass like. Because of this it is not necessary to glaze the object but it is often added for decoration (Science Learning Hub, 2010). Furthermore, stoneware is stronger, more chip-resistant and durable than earthenware and it is watertight so it can be used for outdoor applications (URBANARA UK, 2015). Lastly, stoneware contains impurities giving it a more rough and opaque look.

Porcelain
- High hardness
- Electrically insulating
- Semi-transparent
- High impact strength
- High impenetrability
- Low thermal conductivity

Porcelain is a high-fire refractory clay type. Meaning it is fired at a temperature of between 1200–1450°C. Because it is fired at a very high temperature the objects are fired to the point of vitrification. Resulting in a smooth, glass like surface with very high hardness and translucent properties. Porcelain has a creamy white colour with no impurities. Glazing this material is not necessary but it is often done as decoration (Science Learning Hub, 2010).

Bone china
- High hardness
- Very semi-transparent
- High impact strength
- High impenetrability
- Low thermal conductivity

As porcelain, bone china is a high-fire clay type. However, bone china is not fired at a temperature of 1450°C but at a maximum temperature of 1300°C. What distinguishes bone china from porcelain is that it is already fired to the point of vitrification at bisque firing/first firing which makes the object durable, white and translucent (Narumi, n.d.). The quality of bone china is dependent on the amount of bone ash added to the ceramic mixture. Adding bone ash increases the strength and the whiteness of the object while making it lighter compared to porcelain. Because of the bone ash bone china can be shaped into more thin walled pieces while still having very high hardness, durability and the highest chip-resistance of all the clay based ceramics (TriMark R.W. Smith, 2015).

Without clay

Oxides

- High hardness
- Opaque
- Electrically insulating
- High impact strength
- High impenetrability
- Low thermal conductivity
- Oxidation resistant

Alumina
Zirconia

Non-oxides

- Extreme hardness
- Opaque
- Electrically conducting
- High impact strength
- High impenetrability
- High thermal conductivity
- Low oxidation resistance

Carbides
Borides
Nitrides
Silicides

As mentioned before oxides and non-oxides can be altered or mixed to create composite materials. When this is done the specific properties mentioned above will be combined or improved (Taylor, 2003).

Production

The traditional ceramic manufacturing process is

- Beneficiation
- Batching
- Mixing
- Forming
- Drying
- Firing
    - Bisque firing
    - Glost firing

Not every ceramic type goes through each step. Below it is explained which steps are applicable for which ceramic type.

With clay

Earthenware

Earthenware is used in products which do not require pure state clay. Because of this the clay used is often not treated or optimised during the **beneficiation** step (washing, concentrating and milling (sizing particulates)) (Mason, 2016). Impure clays can be used in an untreated form because they already contain clay minerals, fillers and fluxes. So, it is often used as is but, might be tempered to counteract shrinkage, facilitate uniform drying and decrease the risk of objects cracking during firing (Mississippi Valley Archaeology Center, n.d.).
The batching step (calculating the amounts of oxides according to recipe and weighing them) in this manufacturing process is needed when pure state clay in required. This is not the case for earthenware so the **batching** step is not part of the earthenware manufacturing process.
Before forming, the clay and the tempering ingredients will be **mixed** with a certain amount of water, depending on de forming process, and this will create a uniform distribution inside the water (Mason, 2016). Now the material can be **formed**. There are several forming methods and earthenware can be formed from a lump of clay by pinching, drawing or beating using a paddle and anvil, pressing or pounding into a mould (jiggering and jollying process), building up from coils or slabs and by throwing on a wheel (Tite, 2008). Earthenware can also be slip casted but this does require the **beneficiation** step since the clay needs to be of a purer state so, impurities need to be taken out from the clay (Mason, 2016).
After forming the clay needs to dry. During the **drying** process evaporable water is removed from the clay. As this happens the clay particles are drawn closer together resulting in shrinkage. Drying should be done evenly otherwise stresses are created inside the clay which will eventually show up as cracks or warping. Drying an object evenly is done by ensuring uniform wall thicknesses, drying slowly and even slowing down the drying process at some parts of the object. At the end of the drying step all the water between the clay particles is evaporated but the remaining clay particles are still damp (Big ceramic store, n.d.). Now all the clay particles are in contact and the drying shrinkage is complete entering the leather hard stage.
Now that the object is dried it can be **bisque fired**. Earthenware is a low fire ceramic as mentioned before. During bisque firing the material goes through several stages (Big ceramic store, n.d.).

- It dries completely at 100°C
- The water molecules of the clay are driven off from 350°C to 500°C. Now it is no longer possible to mix the dried clay with water. Irreversible chemical change known as dehydration.
- The quartz crystals rearrange themselves into a slightly different order at 573°C. Causes a slight and temporary increase in volume. When fast firing at this stage of the program cracking often occurs. Change known as Quartz Inversion.
- Organic and inorganic materials are burned off at 900°C.

- The last step of the bisque firing is semi- or full vitrification. Vitrification is the hardening, tightening and finally the partial glassification of the clay. Shrinkage happens during this stage and clays with fine particle sizes will shrink more than clays with larger particle sizes. So, earthenware does not shrink a lot during vitrification. Earthenware firing ends between 1000-1150°C. This is not to the point of vitrification leaving the object quite porous, coarse and low in hardness.

Now that the earthenware object is bisque fired it is often glazed. Earthenware still absorbs water after bisque firing due to its porous properties. Glazing the object will make it watertight (Science Learning Hub, 2010). When it is glazed it has to be fired again to fuse it to the body of the object. This is called **glost firing** (Perry, 2011). This is done at a temperature between 1000-1200°C (Narumi, n.d.).

Stoneware

Stoneware is used in products which do require pure clay and which don't. When impure clay is used the manufacturing process is similar to earthenware but the objects are fired at higher temperatures as mentioned before. Reaching vitrification creating a glass like almost watertight surface which does not need to be glazed (Science Learning Hub, 2010).

Manufacturing process impure stoneware clay:

- Mixing
- Forming
- Drying
- Firing
    - Bisque firing
    - Glost firing (optional)

Often purer state clay is needed when it comes to stoneware so, the **beneficiation** step is needed. Here the clays are washed to either settle out of float off the impurities. Different parts of the clay are removed or separated in different ways. Unwanted minerals can be removed or separated from silicas using gravity, magnetic and electrostatic means and feldspars are washed using floating separation. Here a frothing agent is added to separate the desired material from the impurities (Mason, 2016). After the beneficiation step the previous mentioned manufacturing steps can be executed.

When purer state clay is needed and clay powder is used both the beneficiation and batching steps can be needed. Depending on the needed purity, during **beneficiation**, the clay powder can be milled and washed creating a very fine powder with increased purity (Mason, 2016). After beneficiation the purified powder can be mixed, formed, etc. but, it can also be the case that material properties are needed which require blending. This is done during the **batching** step. During this step the amount of each purified raw material is calculated, weighed, and blended according to recipe (Mason, 2016). After Batching the raw material can be **formed** using the forming methods which are also used when working with earthenware. Stoneware however can also be used for additive manufacturing. This is done by Olivier van Herpt who creates human scale objects from stoneware clay. 3D printing larger objects with stoneware is possible since it is stronger and it will not slump during forming. This would not be possible with earthenware clay or wet clay. After forming the previously mentioned manufacturing steps can be executed resulting in a finalised product.

Porcelain

The porcelain manufacturing process requires almost all steps of the traditional ceramic manufacturing process.

- Beneficiation
- Batching
- Mixing
- Forming
- Drying

- Firing
    - Bisque firing
    - Glost firing (optional)

For porcelain **glazing** is only for decorative purposes. Porcelain starts as an powder and is milled and washed to make it as pure as possible. Afterwards, during the **batching** process, the amount of porcelain powders, silica sands and feldspars are calculated and weighed according to recipe to alter material properties. Thereafter it is **mixed** to the desired consistency depending on the forming method. Porcelain can be **formed** using 4 different methods (Advameg, 2019).

- Soft plastic forming, where the clay is shaped by manual moulding, wheel throwing, jiggering, or ram pressing.
- Stiff plastic forming, here a body is forced through a steel die to produce a column of uniform girth.
- Pressing, compact and shape dry bodies in a rigid die or flexible mould.
- Slip casting, in which a slurry is poured into a porous mould. The excess slurry is filtered out, leaving a layer of solid porcelain inside the mould.

After forming the object has to **dry** and be **bisque fired**.
How the object is bisque fired depends on if it will be glazed or not.
If **glazed**, porcelain will be bisque fired until around a relatively low temperature of 1100°C resulting in a semi-vitrified body. Afterwards, glaze is added to the body and it is glost fired. During glost firing the body is fired at a very high temperature of 1450°C creating a non-porous, glass like, semi-transparent body.
If **not glazed** the porcelain will be fired only once at a very high temperature of 1450°C creating the non-porous, glass like, semi-transparent body right away (Thulasi, 2018).

Bone china
The bone china manufacturing process requires all steps of the traditional ceramic manufacturing process.

- Beneficiation
- Batching
- Mixing
- Forming
- Drying
- Firing
    - Bisque firing
    - Glost firing (optional)

Glazing is purely for decorative purposes and **beneficiation** is not always done. This depends on if the raw materials are purchased with high purity already or not. **Batching** is always part of the bone china manufacturing process since this is the moment all powders are blended and the bone ash is added. Afterwards the blended materials are **mixed** with water to form a slurry with the desired consistency. Now the material can be **formed**. The two most common forming methods are:

- Soft plastic forming, where the clay is shaped by jiggering, or ram pressing.
- Slip casting, in which a slurry is poured into a porous mould. The excess slurry is filtered out, leaving a layer of solid porcelain inside the mould.

And for bone china stiff plastic forming is used mainly as a blank for other forming operations.
After forming the object has to **dry** and be **bisque fired**. The bisque firing step distinguishes bone china from porcelain. During bisque firing the object is fired at a temperature of 1250°C causing it to vitrify already since bone china vitrifies at a lower temperature than porcelain. This makes the object durable, white and more transparent than porcelain. After bisque firing the object is glazed and **glost fired**. This is done at a lower temperature of approximately 1100°C. So, instead of vitrifying the object during glost firing when it is already glazed, like is done with porcelain, the object is already vitrified during the bisque firing.

Without clay

Oxides

For the non-clay based oxides the manufacturing process is as the traditional production process.

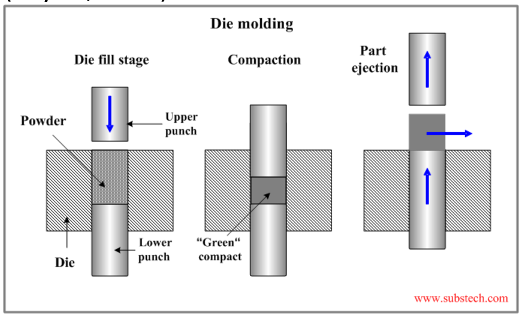
- Beneficiation
- Batching
- Mixing
- Forming
- Drying
- Firing (sintering)
    - Bisque firing
    - Glost firing

Beneficiation and batching are very important steps in the manufacturing process of oxide advanced ceramics. Since the oxide powders used are of very high-purity the slightest amounts of impurities can have dynamic effects on the behaviour of the material when fired for example. Because of this all possibly present impurities are washed off and the powder is milled to decrease the particle size. How fine the particles should be is dependent upon the forming method used. After purifying and milling the oxide powders the batching commences, according to recipe, creating the final slurry. This raw material can be formed in many different ways. These methods can be divided into the categories (Taylor, 2003):

- Dry forming
- Wet forming
- Direct manufacturing

Dry forming

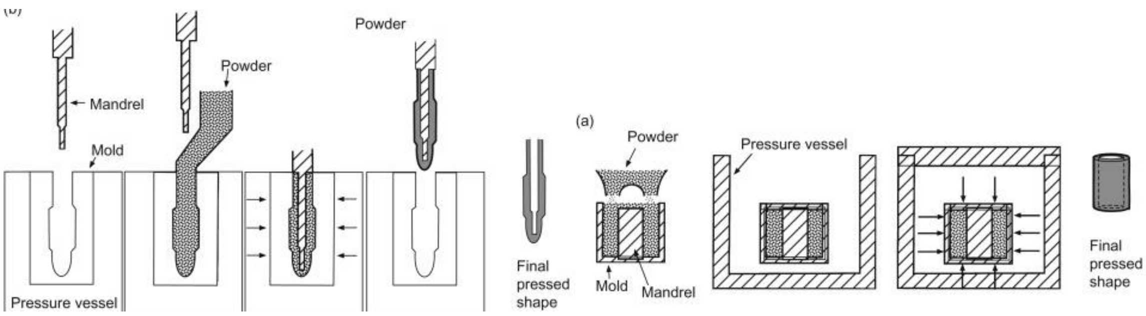
The main advantage of dry forming is that drying after forming is not required. Eliminating the risk of cracking during drying and making the process more rapid since drying of an object can take multiple hours to days. The disadvantage of dry forming is that there is a limitation when it comes to shape complexity. The two dry forming process are uniaxial die pressing and cold isostatic pressing (CIPing) (Taylor, 2003).



Uniaxial die pressing

Here the powders are fed into a uniaxial hollow die. This die typically consist of two opposing pistons or pressing plates. A cross section of this die would be a simple shape such as a cylinder, square, or rectangle. The two opposing pistons or plates move towards each other and pressurize the powder into a green state object. Uniaxial die pressing is generally only used for thin simple shapes, such as tiles. The main disadvantage of uniaxial die pressing is the possibility of nonuniform particle packing. This happens when pressure gradients (difference in pressure throughout area) develop in the pressurized powder during pressing. This can result in nonuniform shrinking during firing, warping/deformation, and cracking during firing (Taylor, 2003).

Cold isostatic pressing (CIPing)



Here the dry ceramic powder is placed inside a thin-walled pre-formed flexible mould, generally made of an elastomer such as latex. When the object is hollow and needs a specific internal geometry it is possible to insert a slider inside the flexible mould. The flexible mould is then sealed and immersed in an oil chamber which becomes subject to pressure. With CIPing more complex shapes are possible compared to uniaxial pressing. Furthermore, nonuniform particle packing is less likely with CIPing so, the objects are less likely to warp/deform and crack during firing.
The disadvantage of CIPing is that there is limited dimensional control. The flexible mould needs to be very thin and have uniform wall thickness but even then there is limited control. The dimensions of objects made from different powder blends but compressed in the same mould differ. So, the powder type has a big influence on the final dimensions of the object (Taylor, 2003).

Wet forming
When using a wet forming technique the formed object needs to dry. This is a disadvantage since there is a risk of cracking during the drying process. Furthermore drying the object is time consuming and costly. Despite this disadvantage powder injection moulding (PIM) is one of the most common production methods, for forming advanced oxide ceramics, to date. The wet forming processes are PIM, tapecasting, slipcasting and extrusion.

Powder injection moulding (PIM)
Here the powder is transformed into pellets. This is done by adding binders to the raw oxide powder, mixing it while hot, cooling it and finally granulating it. The pellets are fed into an injection moulding machine, which is similar to a plastic injection moulding machine. However, the machine and mould need to be resistant or at least largely withstand the erosion from the abrasive binder-oxide powder mix. The pellets are then heated to around 250°C to form a flowable paste which can be injected into the mould under high pressure. The material blend has very high viscosity, even at moulding temperature. After cooling and removal from the mould, the next step is debinding. There is a risk of cracking when the binders are not removed so, this is a critical process. The majority of the binder is dissolved or removed by chemical and/or thermal methods. The residue is then removed during the firing process at the burnout stage (Taylor, 2003).

Tapecasting
Slipcasting
Extrusion

Direct manufacturing
Green machining
Additive manufacturing (3D printing)

Non-oxides

The formation of starting materials and firing for this group, require carefully controlled furnace or kiln conditions to ensure the absence of oxygen during heating as these materials will readily oxidise during firing.

Applications

With clay

The before mentioned classifications of clay based ceramics, earthenware, stoneware, porcelain and bone china, with their different properties result in different applications.

- Earthenware
- Stoneware
- Porcelain
- Bone china
- Fire clay

Earthenware
Earthenware is one of the oldest ceramic types used. It is mainly used in dishware, building bricks, decorative objects and pottery (Billington, 1962).

Stoneware
As said before stoneware is made from refractory clay, has a high hardness, strength and very low water absorption. So it is suitable for facing tiles, floor tiles, mosaic tiles, sanitary ware, refractories, pipes, chemical ceramics, electrical ceramics and household utensils, for example for cooking, baking, storing liquids and as serving dishes (Finishing Materials, 2011) (Thulasi, 2018).

Porcelain
Porcelain is dense, semi-transparent and does not absorb water. Furthermore, it is often decorated with glaze. Because of this porcelain is mainly used in daily tableware, tea sets, sanitary ware, decorative objects called display porcelain, electro technical porcelain and articles of fine arts (Finishing Materials, 2011).

Bone china
Bone china is light, more transparent that porcelain and can be manufactured into thin walled pieces while still maintaining hardness, strength and chip resistance. Because of this bone china is mainly used for tableware, tea sets and decorative objects. (Lenox, 2019)

Without clay

Oxides
electronic devices (Fig. 3), turbocharger rotors (Fig. 4), and tappet heads for use in automotive engines. Other examples of where advanced ceramics are used include oil-free bearings in food processing equipment, aerospace turbine blades, nuclear fuel rods, lightweight armour, cutting tools, abrasives, thermal barriers and furnace/kiln furniture.

Bearings
Bioceramics (medical implants)
Light weight armor
Electrical ceramics (insulators)
Ceramic seals
Cutting tools
Abrasives
Refractories
Moulds
Tubes and pipes
Heating/thermal engineering
Piezo ceramics

Non-oxides
Bearings
Bioceramics (medical implants)
Electrical ceramics (semi-conductors)
Ceramic seals
Cutting tools
Tubes and pipes
Heating/thermal engineering
Forming tools

Appendix B: Formlabs ceramic resin technical characteristics

Impact test

Purpose

Ceramic materials are traditionally brittle and will break when dropped. To understand if this Formlabs ceramic material can withstand being dropped an impact test is executed. The impact test will measure the material's ability to withstand intense force or shock applied over a short period of time. Done by giving an indication on the energy required to break a standard test specimen with one pendulum swing. The impact test helps answering the following questions:

- What is the impact strength of the green state and fired material?
- How does the measured impact strength compare to the information given by Formlabs?
- How does the impact strength of the fired material compare to traditional ceramics?
- How does the impact strength of the green state material compare to traditional polymers?

Method

The test is executed following international standard D256-10 (Determining the Izod Pendulum Impact Resistance of Plastics). However, some alterations were made because of the complex and time consuming production process. Less samples were made and the dimensions of the samples were altered to assure for successfully produced samples.

Both green state and fired state were tested. 3 samples of fired ceramics (specimen 1-3) and 2 samples of green state ceramics (specimen 4-5) were tested. The samples were accurately measured before testing (height, width, depth) to ensure for a proper comparison. The average depth of the samples is
Green state ceramics: 12.04 mm
Fired ceramics: 10.383 mm
And the average width of samples is
Green state ceramics: 6.87 mm
Fired ceramics: 6.07 mm
The samples were printed horizontally, so the pendulum will hit the samples perpendicular to the printed layers.
A Zwick Izod pendulum impact tester was used to execute the test.

Results

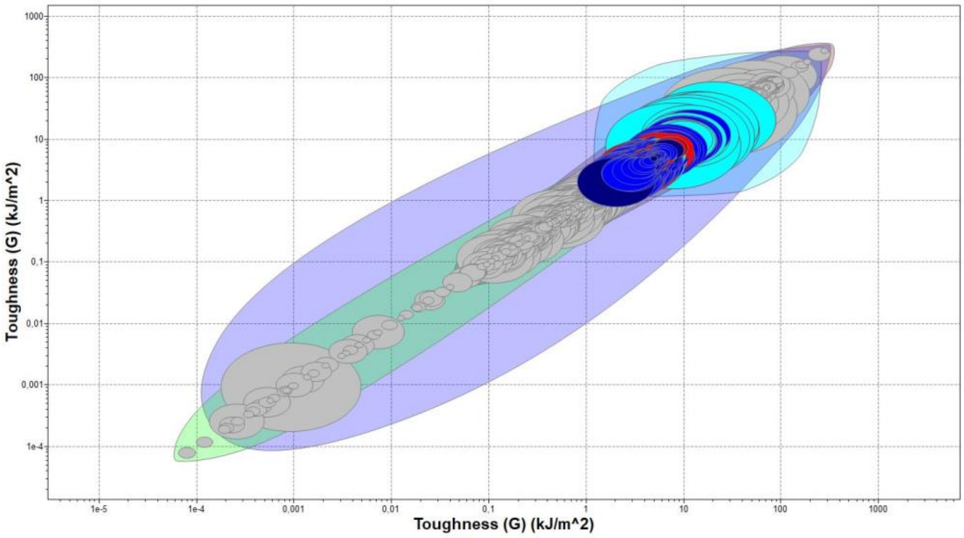
All samples successfully broke meaning a break where the sample separates into two pieces.
The measured impact resistance for each specimen is
Specimen 1: 2.4 kJ/m^2
Specimen 2: 2.3 kJ/m^2
Specimen 3: 2.3 kJ/m^2
Specimen 4: 5.7 kJ/m^2
Specimen 5: 6.0 kJ/m^2
The average impact resistance measured for the green state material is 5.85 kJ/m^2.
The average impact resistance measured for the fired material is 2.33 kJ/m^2.
Formlabs presents the impact resistance in J/m so, kJ/m^2 will be converted to J/m. The new results are.
Green state ceramics: 5.85 kJ/m^2 * 0.01204 = 70.4 J/m
Fired ceramics: 2.33 kJ/m^2 * 0.010383 = 24.2 J/m

Discussion

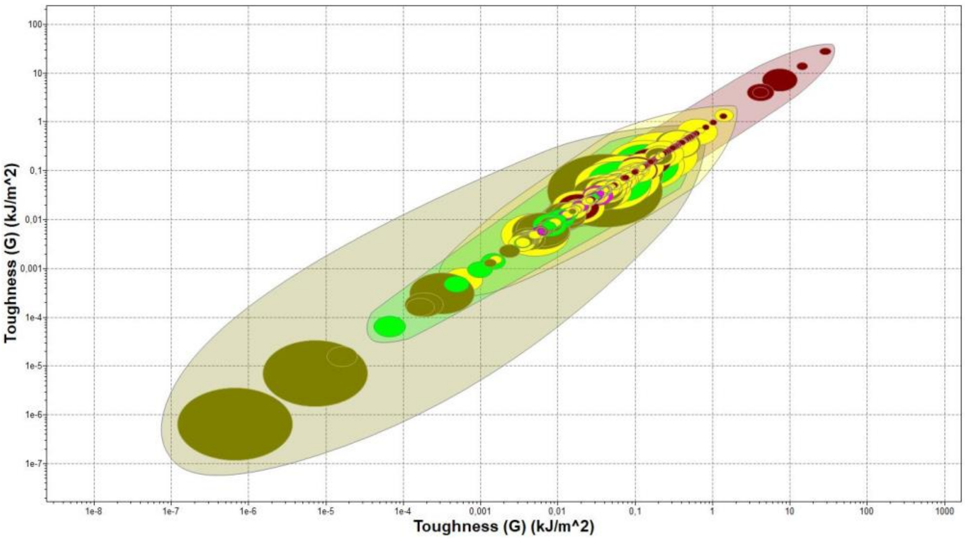
The measured impact resistance for the green state material was compared to the data gathered by Formlabs. The green state results of the impact test are not comparable to the Formlabs data at all (green state = 18.42 J/m). This can be because of the printing direction. As said, the pendulum swung perpendicular to the printed layers requiring more energy than when swung parallel to the layers. The green state material has a medium impact resistance in comparison to other polymers. It is comparable to lots of other plastics and elastomers. So, the impact resistance does not make the material unique.

The fired material actually has a high impact resistance in comparison to other ceramics, both traditional and advanced (CES Edupack). The Formlabs material can resist impact as well as advanced and composite ceramics. Its impact toughness is comparable to the impact toughness of high translucent Zirconia (ZrO_2), which is used for dental crowns, cutting tools and bearings. So, the material is definitely better fit for impact applications compared to traditional ceramics. However, it is still a ceramic material so rubbers, materials, and soft plastics are of course still better fit for impact applications.

Impact toughness of green state ceramics compared to plastics.



Impact toughness of fired ceramics compared to other ceramic materials.



Tensile test

Purpose

Ceramic materials generally have a low strength. To test if this is also the case for the Formlabs material tensile tests are executed. This is done by measuring the tensile stress that can be applied on the material sample before it permanently deforms (yield strength) or breaks (tensile strength) (Corrosionpedia, n.d.). The sample will return to its original shape if a stress level is applied which is lower that the yield strength. The sample will be permanently deformed when the stress level applied exceeds the yield strength. The sample will break when the applied force exceeds even the tensile strength. The test will provide the answers on the following questions:

- What is the tensile strength of the green state and fired material?
- How does the measured tensile strength compare to the information given by Formlabs?
- How does the tensile strength of the fired material compare to traditional ceramics?
- How does the tensile strength of the green state material compare to traditional polymers?

Method

The test is executed following international standard D638-14 (Tensile Properties of Plastics). However, some alterations were made because of the time consuming production process and the size restriction of the printer. Less samples were made and the dimensions of the samples were altered to assure for successfully produced samples.

Both green state and fired state were tested. 4 green state specimen were tested (1-4) and 3 fired specimen were tested (5-7). The samples were accurately measured before testing (height, width, thickness) to ensure for a proper comparison. The average area of the green state specimen is 43,035 mm^2 and the average area of the fired specimen is 36,580mm^2 . The samples were printed horizontally, so the tensile testing machine will exercise the pulling force parallel to the layers.
A Zwick Roell Z010 tensile testing machine was used to execute the test.

Results

Only the green state samples were successfully put through the test and successfully broke. The fired samples had slight warping which made it impossible to properly secure them between the fixed grips. The samples would break before they could be properly clamped in. So, when executing the tensile test the samples would slip out of the grips rather than actually being subject to tensile stresses.
The measured force at break for each specimen is
Specimen 1: 238,7 N
Specimen 2: 231,1 N
Specimen 3: 228,7 N
Specimen 4: 236,8 N
Specimen 5: 0 N
Specimen 6: 0 N
Specimen 7: 0 N
Since the results of the green state ceramics were accurate the tensile strength (σ_U), Young's modulus (E) and strain at break (ε_U) were calculated.
Tensile strength is calculated with the following formula.

$$\sigma_U = \frac{\mathrm{W}}{A_0}$$

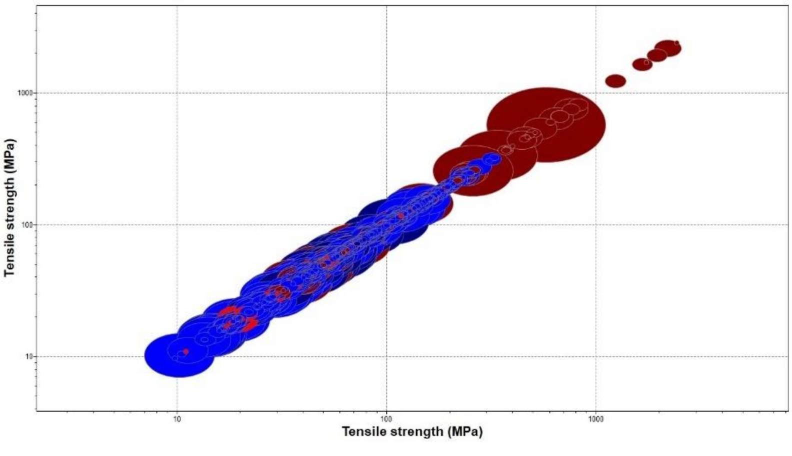
The Young's modulus is calculated with the following formula

$$E = \frac{\sigma_U}{\varepsilon_U}$$

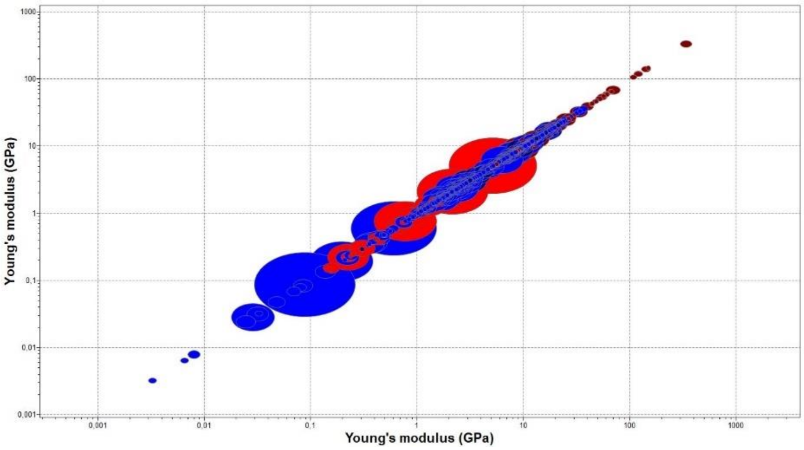
The tensile strength for each specimen is
Specimen 1: 5,55 Mpa

Specimen 2: 5,37 Mpa
Specimen 3: 5,31 Mpa
Specimen 4: 5,50 Mpa
The Young's modulus for each specimen is
Specimen 1: 0,24 Gpa
Specimen 2: 0,24 Gpa
Specimen 3: 0,23 Gpa
Specimen 4: 0,24 Gpa
The measured strain at break for each specimen is
Specimen 1: 0,02
Specimen 2: 0,02
Specimen 3: 0,02
Specimen 4: 0,02
The average tensile strength measured for the green state material was 5.43 MPa and the average Young's modulus measured was 0.24 GPa.

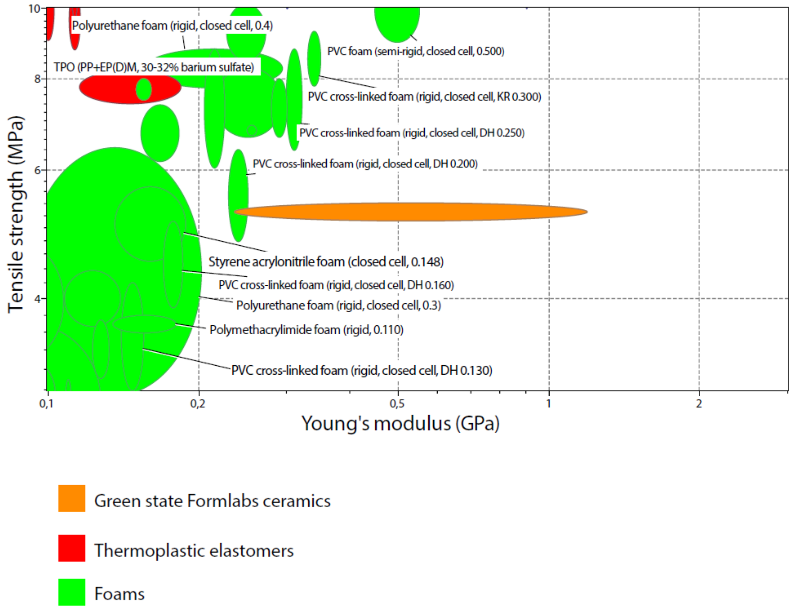
Discussion
The measured tensile strength and Young's modulus for the green state material were compared to the data gathered by Formlabs. The measured tensile strength is comparable to the Formlabs data, so this confirms that the test was executed correctly. The Young's modulus is lower compared to the data made available by Formlabs (Young's modulus = 1.03 GPa). This means that measured strain is significantly different. This could be caused by a different print orientation but this is unsure and should be tested.

The green state Formlabs material has a low tensile strength and Young's modulus compared to other polymers. Meaning it is low in strength and low in stiffness compared to other plastics. This exact combination of tensile strength and Young's modulus is however unique and is not comparable to anything.
Since it was not possible to execute this test for the fired material a 3 point bending test was executed afterwards.
Tensile strength of green state ceramics compared to plastics.


Young’s modulus of green state ceramics compared to plastics.



Tensile strength and Young’s modulus of green state ceramics compared to polymer materials.



3 point bending

As said ceramic materials generally have a low strength. Since It was not possible to measure the strength of the fired material using the tensile tests, 3 point bending tests are now executed. The type of strength measured during this test is the flexural strength. The flexural strength is the amount of force or stress an object can withstand before breaking or permanently deforming (Johnson, 2018). The test will provide the answers on the following questions:

- What is the flexural strength of the green state and fired material?
- How does the measured flexural strength compare to the information given by Formlabs?
- How does the flexural strength of the fired material compare to traditional ceramics?
- How does the flexural strength of the green state material compare to traditional polymers?

https://sciencing.com/calculate-flexural-strength-5179141.html

Method

The test is executed following international standard D790-03 (Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials). However, some alterations were made because of the time consuming production process and the size restriction of the printer. Less samples were made and the dimensions of the samples were altered to assure for successfully produced samples.

both green state and fired state specimen were created to be tested. 3 green state specimen were tested (1-3) and 3 fired specimen were tested (4-6). The samples were accurately measured before testing (height, width, thickness) to ensure for a proper comparison. The average thickness of the green state specimen is 2,85 mm and the average width of the green state specimen is 11,75 mm. The green state specimen were tested with a support span of 40 mm. The average thickness of the fired specimen is 2.45 mm and the average width of the fired specimen is 9.45 mm. The fired state specimen were tested with a support span of 34 mm. The samples were printed horizontally, so the 3 point bending testing machine will exercise the pushing force perpendicular to the layers.
A Zwick Roell Z010 3 point bending testing machine was used to execute the test.

Results

Here testing with the fired specimen created no complications and all results were accurate. All samples successfully broke, meaning a break where the sample separates into two pieces.
The measured force at break for each specimen is shown below
Specimen 1: 14,37 N
Specimen 2: 13,72 N
Specimen 3: 15,17 N
Specimen 4: 31,42 N
Specimen 5: 25,89 N
Specimen 6: 28,12 N
With these results the modulus of elasticity (E), flexural stress (σf) and flexural strain (ϵf) are calculated.
The modulus of elasticity or flexural modulus is calculated with the following formulas

$$E = \frac{L^3 m}{4bd^3}$$

$$m = \frac{F}{dL}$$

The flexural stress or flexural strength is calculated with the following formula

$$\sigma f = \frac{3PL}{2bd^2}$$

Lastly the flexural strain is calculated with the following formula

$$\epsilon f = \frac{6Dd}{L^2}$$

The m and flexural modulus at break for each specimen are
Specimen 1 m: 11,24 N/mm
Specimen 1 E: 0,661 GPa
Specimen 2 m: 9,93 N/mm
Specimen 2 E: 0,584 GPa
Specimen 3 m: 10,15 N/mm
Specimen 3 E: 0,597 GPa
Specimen 4 m: 337,79 N/mm
Specimen 4 E: 23,88 GPa
Specimen 5 m: 321,94 N/mm
Specimen 5 E: 22,76 GPa
Specimen 6 m: 306,21 N/mm
Specimen 6 E: 21,65 GPa
The flexural strength at break for each specimen is
Specimen 1: 9,04 MPa
Specimen 2: 8,63 MPa
Specimen 3: 9,54 MPa
Specimen 4: 28,25 MPa
Specimen 5: 23,28 MPa
Specimen 6: 25,29 MPa

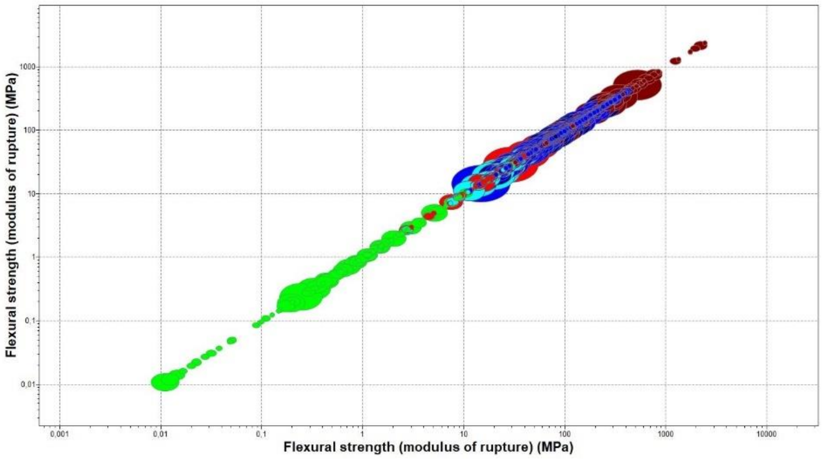
The flexural strain at break for each specimen is
Specimen 1: 0,057
Specimen 2: 0,060
Specimen 3: 0,058
Specimen 4: 0,038
Specimen 5: 0,037
Specimen 6: 0,037
So the average flexural strength, flexural modulus and flexural strain at break for the green state material is
σf = 9,07 Mpa
E = 0,61 GPa
ϵf = 0,058
And the average flexural strength, flexural modulus and flexural strain at break for the fired material is
σf = 25,61 Mpa
E = 22,77 GPa
ϵf = 0,037

Discussion
The measured flexural strength and flexural modulus for both materials were compared to the data made available by Formlabs. Both the measured flexural strength and flexural modulus of the green state material are comparable to the Formlabs data, so this confirms that the test was executed correctly. The flexural strength of the fired material was lower compared to the data made available by Formlabs (flexural strength = 33.5 MPa). This could be caused by a different print orientation but this is unsure and should be tested.

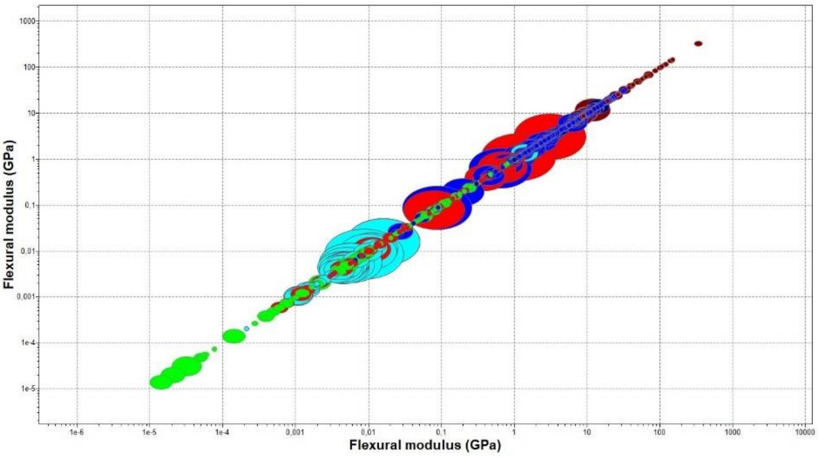
The green state Formlabs material has a very low flexural strength compared to other polymers. The flexural strength of the material is lower than all plastics and is more comparable to the flexural strength of foams. The flexural modulus of the green state material is also low compared to other polymers. However, there are still several plastics with a comparable flexural modulus. So, the green state material had a very low strength and is flexible but not as flexible as rubber or foam.

The fired Formlabs material has a low flexural strength compared to other ceramic materials. The measured strength is a bit higher than traditional ceramics but lower than most advanced ceramics and composites. The flexural modulus of the fired Formlabs materials is low compared to other ceramic materials. Most traditional and advanced ceramics have a higher flexural modulus. So, the fired material had a low strength and is quite flexible for a ceramic material.

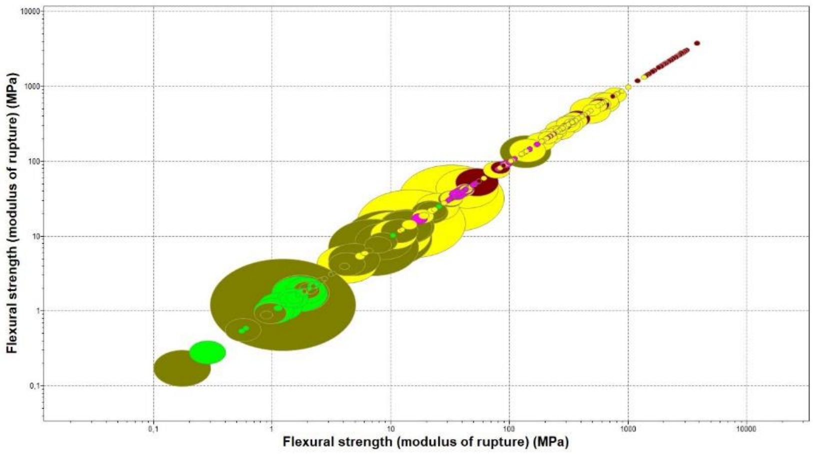
Flexural strength of green state ceramics compared to polymer materials.



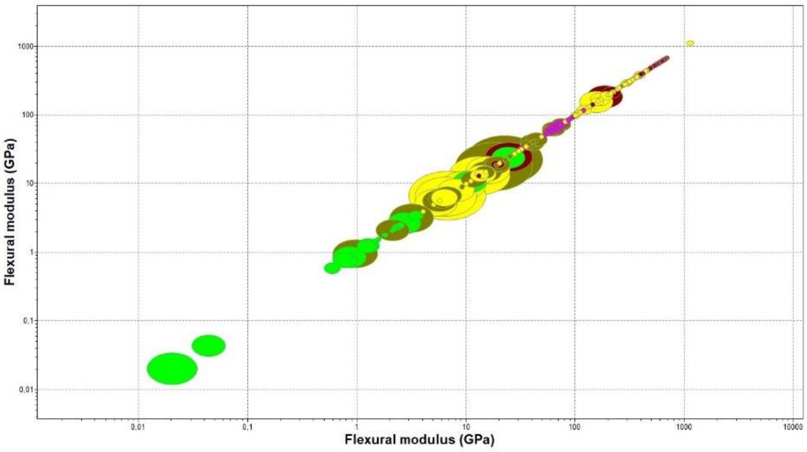
Flexural modulus of green state ceramics compared to polymer materials.



Flexural strength of fired ceramics compared to ceramic materials.



Flexural modulus of fired ceramics compared to ceramic materials.



Appendix C: Printing findings

Before actually starting with printing and firing the guide made available by Formlabs was read. This guide contains a list of printing and firing tips and this was the basic for this explorations phase. During the exploration certain steps were altered or added to make the manufacturing process more successful.

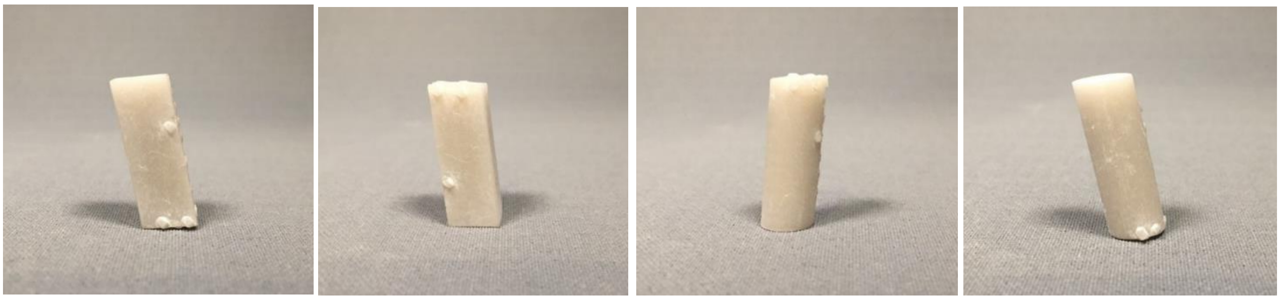
After reading the tips the first step in exploration was to be able to successfully print an object using the new ceramic material and the SLA printing technique. This was possible after 4 test prints.

So final do's for printing with the Formlabs ceramic material are:
- Sand the build plate with 150 sanding paper
- Mix the resin inside the resin tank
- Shake the resin cartridge
- Check if the resin sensor is clean
- Orient the part either horizontally or vertically not in an angle.
- Use enough support both in density and thickness of the support touchpoints. Preferably support beams with a touchpoint size of 2 mm.

When printing beams it is possible that they are printed with a deflection. To prevent this from happening make sure the model has enough support. High density and a touchpoint size of 2 mm.

Model should not be printed in an angle
Each new layer is stuck to both the model and the resin tank bottom
Movement of the resin tank releases the layer from the bottom of the tank
Force increases when area increases
Insufficient support will eventually lead to printing failure and model dropping in tank
Support size should be at least 2.00 mm thick
Wire like models should be avoided

Build plate should be sanded firmly and cleaned afterwards to remove metal particles
It is possible to print models directly on the build plate
Have a big area so should not be thicker than 2,5 mm or it releases from the build plate
Even after sanding the sample the support points stay visible



Model is printed in a wrong way (figure 1). The top and bottom face of the model are not perpendicular to the other faces anymore. This is caused by a combination of the build plate moving upwards, the resin tank moving sideways and printing the model in an angle.

Why is this not a problem for the other materials?
Material is brittle so when printing high, thin wire like models it can happen that the model releases itself from the support and drops in the resin tank.

Why is the support printed correctly but the model isn't? Is it because the model is placed in an angle and the support isn't? Printing a drawbar in a straight position now to test this.



New models which were printed horizontally also failed so now I know that the material is released from the support because the cross sectional area of the model was to excessive in combination with the material being brittle. One model which was printed vertically also failed here the cross sectional area was not too excessive so this probably failed because of Insufficient support.

The vertically printed models did print correctly. The horizontally printed models did have flaws. It looks like it was not supported correctly and because of this the models show deflection.

Impact samples are printed and now with support beams with a thickness of 2 mm instead of 1.40. this print succeeded. It was printed horizontally so it also had quit an excessive cross sectional area but the model had sufficient support so the print was a success.

Appendix D: Firing findings

The next step in the exploration was to be able to successfully fire objects. This means firing an object without cracking, warping and with a smooth glass like finish. This was possible after 5 test firings. The findings acquired during these test firings are:

Burnout hold of 1 hour per 1 mm wall thickness is way too short
5 mm samples were fired with a burnout hold of 8 hours and no cracks occured
Burnout hold should be at least 1.5 hours per 1 mm wall thickness
Wall thickness should not be more than 5 mm
Samples with the correct burnout hold have a slightly rough vitrified glass like surface
No structural cracking has occured so, cooling down settings are correct

Appendix E: Focus group

Purpose

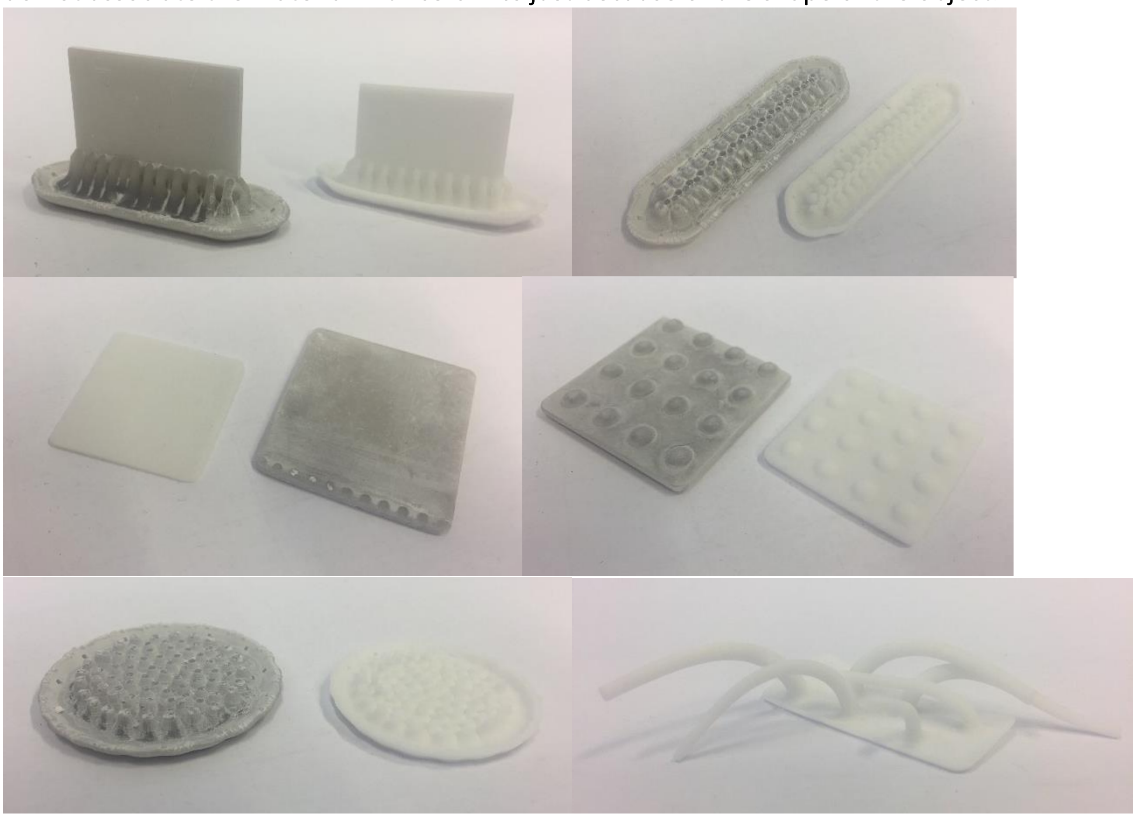
The purpose of this focus group was to understand how the material is experienced by people. It will create understanding about how the material is received by people and what it makes people do based on four different experiential levels: sensorial, interpretive (meanings), affective (emotions), and performative (actions, performances) (Giaccardi and Karana, 2015). These levels will create an understanding of the material experience, categorized in four different experiential qualities. However, these material experience levels are intertwined and experienced as a whole, influenced by each other, time and the context of use (Karana, Pedgley and Rognoli, 2014; Giaccardi and Karana, 2015). The results from the focus group will provide guidance on how people are likely to experience and interact with a particular material when applied in a future product and will give inspiration during the ideation phase of the project.

Participants

5 participants joined the focus group whereof 60% male and 40% female. 4 participants were 24 years and 1 was 29 years old. All were IDE students, since there was no specific target group and this target group was easily accessible for the designer. Lastly there were snacks and drinks available during the test as a thank you.

Stimuli

11 different samples were used for this test. 5 pairs of an unfired and fired sample in different shapes and sizes and 1 organically shaped fired sample. These particular shapes were chosen because they do not resemble objects which are currently made from ceramics, like cups for example. Using neutral and organic shapes, which do not resemble any products on the market, ensures that people do not associate the material with ceramics just because of the shape of the object.



Besides the 11 samples a semantic differential scale was used (Osgood et al., 1957). On this scale pairs of polar adjectives are listed. Using these adjectives the meaning of the material can be measured. The participants will communicate their attitude towards the material by choosing positions on the scale. The semantic differential scale used for this test can be found in appendix G.

To be able to measure the sensorial properties of the material a list of sensory terms was used. This list contains sensorial properties which are more commonly used to assign meaning to materials (Karana et al., 2009). These specific sensorial properties are listed in appendix F.

Apparatus

The focus group was held in the Product Evaluation Lab (PEL) at the faculty of IDE. This room is equipped with two camera's which are placed opposite from each other. These cameras record the participants during the focus group from two different sides capturing everything that is happening. The room is also equipped with multiple microphones which record everything that is said during the focus group.

Procedure

The focus group was made up out of 2 rounds. During the first round the participants explored the green state material (unfired) and during the second round the participants explored the fired material.

Round 1: Green state material

Visual experience

The green state material was first experienced visually. The participants got some time to explore all samples and afterwards they were asked to communicate the sensory characteristics of the material by filling in the sensorial property scales. When they filled in the sensory form they were asked to fill in the semantic differential scale.
When all forms were filled in the test conductor started the discussion allowing everyone to explain what they filled in and why.

Complete experience

The participants were allowed to touch the samples when all points from the visual exploration were discussed. The participant got time to explore the samples and after the tactual exploration they were asked to fill in the sensorial property form and the semantic differential scale again.
When all forms were filled in the test conductor started the discussion where the participants could explain what they filled in, if anything changed and why.

Round 2: Fired material

Visual experience

During round two the participants explored the fired samples. As for the green state samples the fired samples were first explored visually. After the visual exploration the participants were asked to fill in the sensorial property form and the semantic differential scale.
When all forms were filled in the test conductor started the discussion again where the participants could explain what they filled in and why.

Complete experience

Lastly the participants were allowed to touch the samples when all points from the visual exploration were discussed. The participant got time to explore the samples and after the tactual exploration they were asked to fill in the sensorial property form and the semantic differential scale again.

When all forms were filled in the test conductor started the discussion where the participants could explain what they filled in, if anything changed and why.

Measures

The focus of this research was to understand how the material is experienced by people. This understanding is created by measuring people's attitude towards the four different experiential levels: sensorial, interpretive (meanings), affective (emotions), and performative (actions, performances).

Sensorial

The sensorial experience is measured using a set of sensorial properties which are grouped under different sensory terms (Karana et al., 2009). (appendix F) The participants can communicate the perceived sensory characteristics of the material using this list of sensory properties.

Interpretive

Measuring this level will create understanding about the experienced meaning of the material. The meaning of the material is measured using the sematic differential scale. The participants will choose positions on the scales to communicate their attitude towards the material. The polar adjectives were chosen because of their possible relevance for this material. The interpretive level will also be measured by documenting all the associations mentioned by the participants during the focus group.

Affective

The affective experience level signifies the emotions felt when experiencing the material. Measuring this level will be done by observing the participants and documenting how the participants react to the visual and tactual stimulations and what they say.
For example, the first reactions of the participants will be recorded when they are allowed to touch the material after the visual exploration.

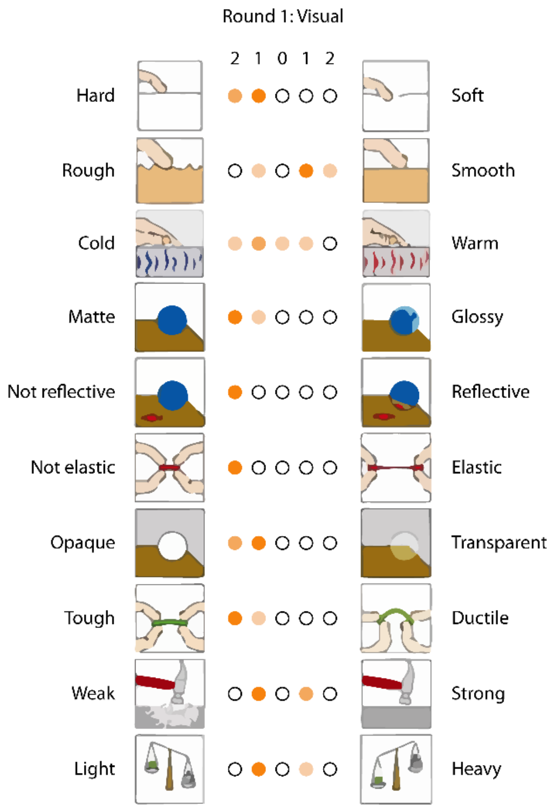
Performative

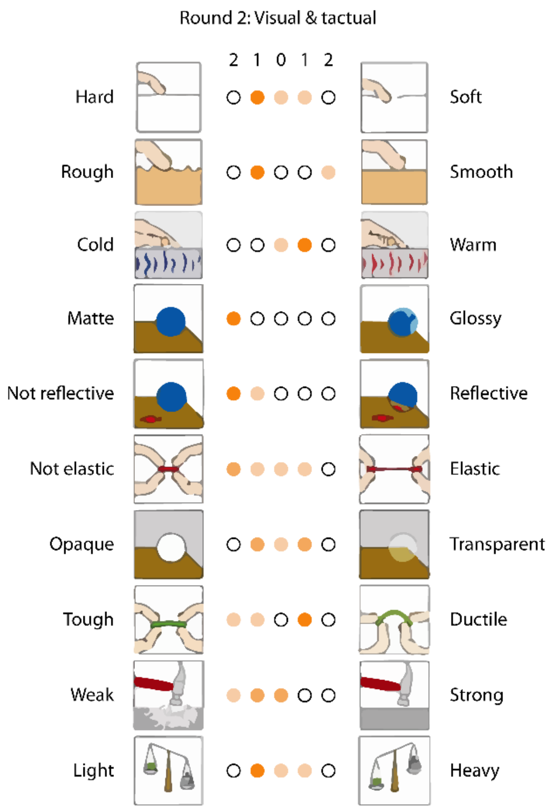
The performative experience level signifies how the participants act and perform when interacting with the material. This level will be measured by observing the participants and documenting what they do to the material.

Results

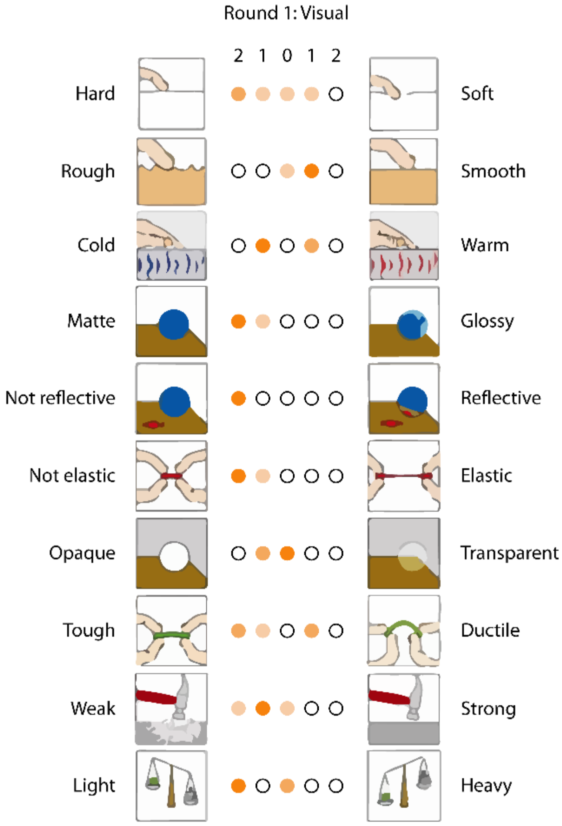
Sensorial

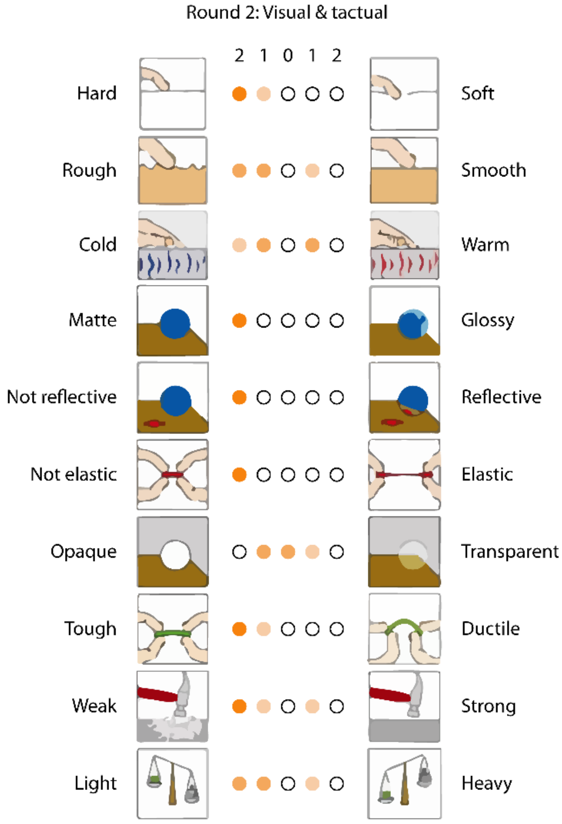
Round 1: Green state material





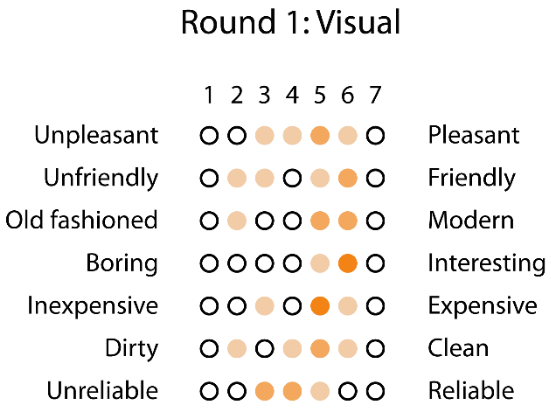
Round 2: Fired material

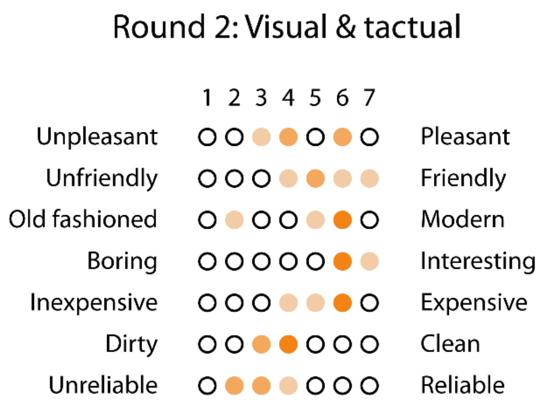


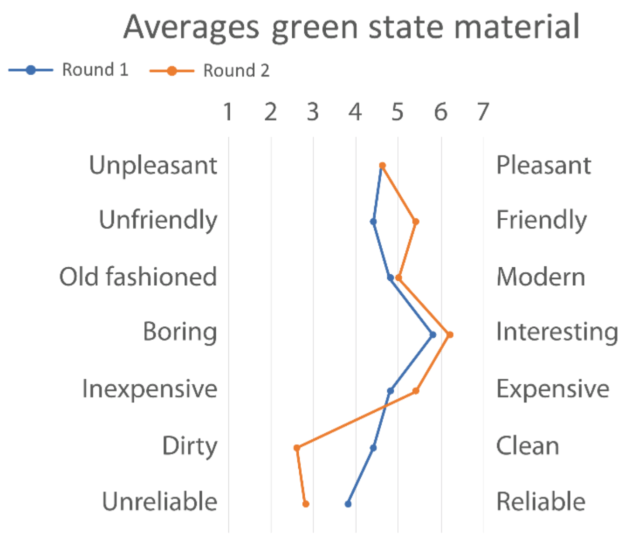


Interpretive

Round 1: Green state material



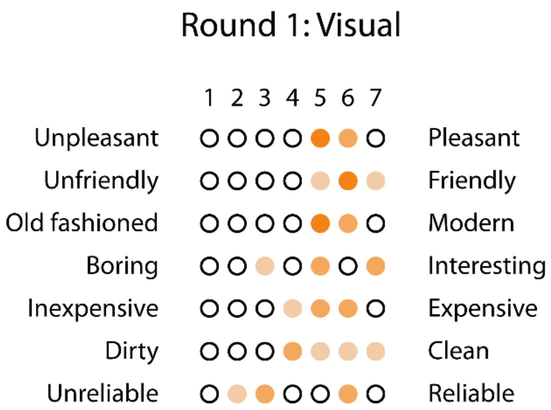


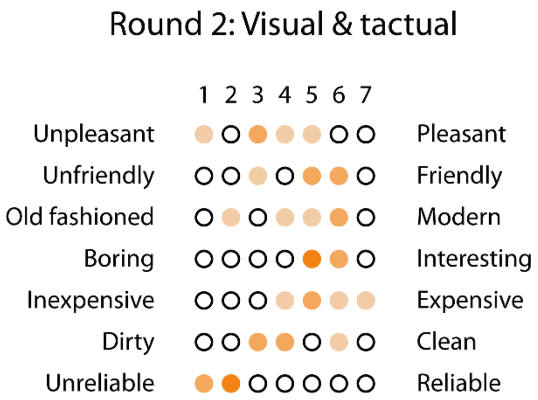


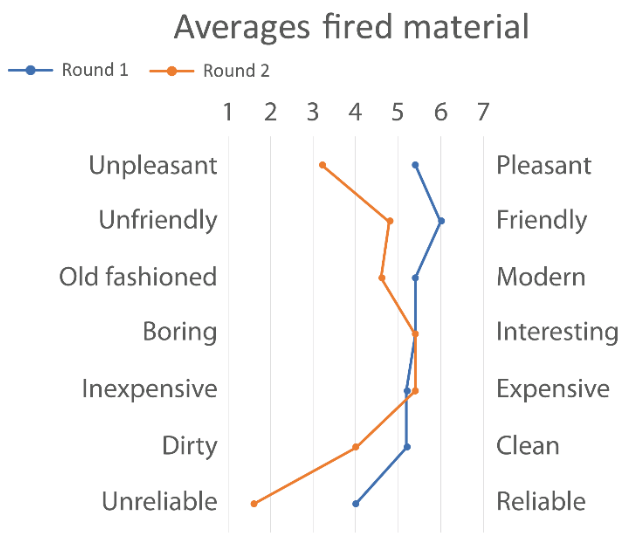
When only exploring the green state material visually some of the participants experienced it as friendly and pleasant. This was because the powder layer on the material was associated with velvet or a silky-smooth material. The material was also associated with a stone which would be used in a sauna or some sort of soft stone in general. There were also participants which found the material less friendly and pleasant because they associated the material with something cold like a surgery room or a marble floor.

When actually touching the material the participants experienced the green state material as dirty because of the residue is leaves behinds on the hands. This residue also made the material less reliable. The translucency also became for visible during the tactual exploration and since the material is rather translucent it was associated with milky glass.

Round 2: Fired material







During the visual exploration the participants experienced the fired material as pleasant and friendly. This was because it looked soft and the white colour of the material gives it a fresh and pure appearance. The pureness and freshness of the material also made the material look modern according to the participants. Furthermore, the fired material was found less interesting than the green state material because it was associated with known objects like bathroom tiles and old tableware.

When touching the fired material the participants experienced it as unpleasant, less friendly and dirty because of the unexpected roughness. It also became less modern because the participants associated it with ceramics, a nail vile, chalk boards and sanding paper. Lastly the material was experienced as unreliable because it was associated with ceramics and felt brittle but also because of the visible cracks.

Affective

Round 1: Green state material

The green state material elicits several emotions. When only exploring it visually the participants mentioned that they would want to touch it and that they feel attraction and curiosity towards it. They also expected the samples to feel soft and velvet like which gave them the feeling of pleasure.

When touching the samples the participants were surprised that it was rough. For one participant this was a positive surprise since it was still experienced as pleasant but different. For most participants it was experienced as a negative surprise because of the unexpected roughness.

All participants found the material dirty because of the residue which was left behind on the hands after touching the samples. They would try to clean their hands by rubbing them together. This sensation of a residue left on their hands created doubt because they were not sure if it was harmful. The residue and the roughness also created a feeling of disgust which was communicated by uncomfortable looks and cries.

The fact that the material leaves a residue makes it unclear what type of material it actually is and this creates a feeling of fascination when exploring it.

Lastly the material created a feeling of distrust because it was easier to break than expected.

Round 2: Fired material

The fired material also elicits several emotions. During the visual exploration it became clear that the participants found this material visually pleasing and friendly creating a feeling of pleasure and calmness. The material was also experienced as less interesting since it was comparable to known materials. The fact that it looks recognisable created the feeling of slight boredom and also of comfort and calmness.

When actually touching the material all participants were surprised because it felt rougher than expected. This surprise was a negative surprise for all participants. None of the participants found it a pleasant experience and this created a feeling of discomfort for all participants.

All participants communicated this discomfort with uncomfortable looks, cries and even goose bumps and they all felt disapproval towards the material and its roughness. Two participants even felt disgust when touching the samples and this sensation was so intense that it created a pullback reaction resulting in the participants dropping the samples.

The last emotion felt was distrust. This was felt because of the visible cracks in the samples but also because of the unexpected roughness. The participants thought they could predict what it would feel like when looking at it but the actual sensation was completely different.

Performative

Round 1: Green state material

Hold in the light
Stroking surface
Lightly bending
Dropping on the table to here sound it makes
Bending back and forth
Unintentionally breaking
Pressing nail into surface
Rubbing fingers together after touching
Rubbing hands together after touching
Smelling hands after touching

Round 2: Fired material

Dropping it on the table (sample with dots)
Releases it and it false pull back reaction (sample with dots)
Stroking surface
Stroking sample on palm of hand
Scratching the surface
Inspect the thickness of the part
Holding samples with caution between finger tips
Hold in the light
Hold in light and place finger behind it
Placing it back on the table very carefully
Placing on palm of hand (sample with support) (cold and warmth)
Weighing it by holding it between fingers and moving it up and down
Trying to break by bending
Breaking by bending

Discussion

Round 2: Fired material

Sensorial

The participants mentioned that the mat surface of the material makes it looks soft while it actually is a hard material. So, maybe people associate mat to soft and glossy to hard.
The material has no visible textures and is white with no impurities so participants expect it to be smooth while it actually is rough. This creates an incongruence between senses. This incongruence can be removed by making the material either look rough and feel rough or look smooth and feel smooth.
The high translucency of the material was only visible when held in the light or when covering something (finger). So, this is why it was not visible for all participants during the visual exploration.
The participants expected the material to be more ductile than it actually is. This could be because the mat surface makes it look more like plastic than ceramics but this is not sure.

Interpretive

The meaning of the material was very positive during the visual exploration because it was friendly, aesthetically pleasing, clean, reliable and modern. But when touching the material the meaning became more negative. It became less friendly, unpleasant, dirtier, unreliable and less modern. So, this material should be used in a visual product or the meaning should be altered.
The material was found less interesting than the green state material because it was recognisable. This recognition can bring comfort and confidence but also boredom so it might be nice to change the meaning of the material into more interesting.

Affective

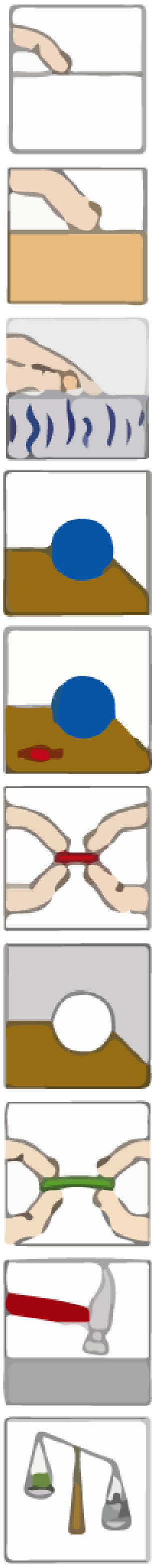
The emotions felt during the visual exploration are in general positive. Emotions like pleasure, calmness and comfort were felt but also light boredom because of its recognisable aesthetic. However, the emotions felt during the complete exploration became negative. Emotions like negative surprise, discomfort, disapproval, disgust and distrust were felt.

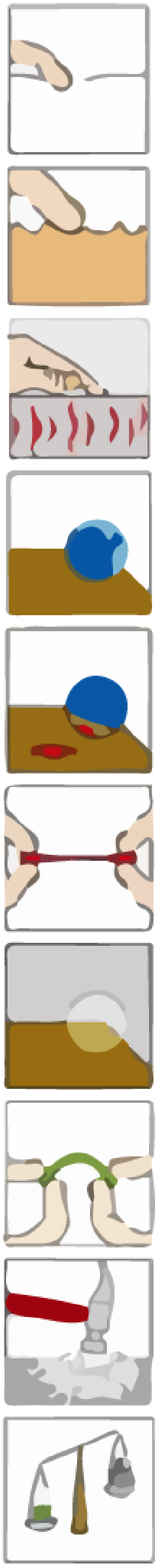
The aesthetic properties of the material elicited the positive emotions. And the negative emotions were mostly caused by the unexpected roughness of the material and the visible cracks. So, the material should have a complete positive affective experience when the incongruence between senses is removed.

Performative

Stroking and scratching of the material was used to be able to explore the texture of the material. Holding the samples in the light or placing fingers behind it was used to explore the translucency of the material. Every participant held and handled the samples with caution. They were held between finger tips and placed back on the table very carefully. The participants also mentioned a lot that they were afraid of breaking it. One participant became less cautious with time. Eventually dropping the samples on the table repeatedly to test the strength of the material and to explore the sounds it makes. All participants had the urge to bend the samples. This was probably to test when they would break. Some of the participants also mentioned that they had the urge to break it and at the end some participants broke some samples.
None of the participants linked the two materials together

Appendix F: Sensorial properties focus group





	2	1	0	1	2	
Hard	○	○	○	○	○	Soft
Smooth	○	○	○	○	○	Rough
Cold	○	○	○	○	○	Warm
Matte	○	○	○	○	○	Glossy
Not reflective	○	○	○	○	○	Reflective
Not elastic	○	○	○	○	○	Elastic
Opaque	○	○	○	○	○	Transparent
Tough	○	○	○	○	○	Ductile
Strong	○	○	○	○	○	Weak
Light	○	○	○	○	○	Heavy

Appendix G: Semantic differential scale focus group

	1	2	3	4	5	6	7	
Unpleasant	○	○	○	○	○	○	○	Pleasant
Unfriendly	○	○	○	○	○	○	○	Friendly
Old fashioned	○	○	○	○	○	○	○	Modern
Boring	○	○	○	○	○	○	○	Interesting
Inexpensive	○	○	○	○	○	○	○	Expensive
Dirty	○	○	○	○	○	○	○	Clean
Unreliable	○	○	○	○	○	○	○	Reliable

Appendix H: Interview

Hoelang beoefent ellen de kunst keramiek al?

Waarom beoefent ellen de kunst keramiek?

Ze heeft nu een atelier hoe lang heeft ze die al en heeft ze alleen gekeramiekt in eigen atelier of ook bij andere bedrijven/ateliers etc.

Wat vind ellen het leukst om te doen in het gebied keramiek?

Wat is de specialisatie van ellen?

Zelf geëxperimenteerd tijdens het productie proces en/of met het materiaal?

Zo ja wat, waarom en welke variabelen moeten bekend zijn wil je kunnen experimenteren?

Welke eigenschappen zorgen ervoor dat ellen zich aangetrokken voelt tot de klei/keramiek en welke klei zorgt hier het meeste voor en waarom?

Welke klei soort werkt ellen liever niet mee en waarom?

Is er een klei soort waar ellen nooit mee heeft gewerkt zo ja welke en waarom?

Is er een klei soort waar ellen nog mee zou willen werken zo ja welke en waarom?

Eigenschappen hiervan?

Productie proces per klei soort?

Green state, oven fase, na oven etc.

Uitdagingen tijdens productie?

Het nieuwe materiaal

Met welke klei soort is het materiaal het meest vergelijkbaar als het überhaupt vergelijkbaar is?

Naar welke eigenschappen van dit materiaal kijkt ze om het te kunnen vergelijken met keramiek?

Vul semantic differential scale in voor klei soort die ellen vergelijkbaar vind aan 3d keramiek

	1	2	3	4	5	6	7	
Unpleasant	○	○	○	○	○	○	○	Pleasant
Unfriendly	○	○	○	○	○	○	○	Friendly
Old fashioned	○	○	○	○	○	○	○	Modern
Boring	○	○	○	○	○	○	○	Interesting
Inexpensive	○	○	○	○	○	○	○	Expensive
Dirty	○	○	○	○	○	○	○	Clean
Unreliable	○	○	○	○	○	○	○	Reliable

Doet het je aan een ander materiaal denken dus niet perse keramiek?

Vul semantic differential scale in voor 3d keramiek

	1	2	3	4	5	6	7	
Unpleasant	○	○	○	○	○	○	○	Pleasant
Unfriendly	○	○	○	○	○	○	○	Friendly
Old fashioned	○	○	○	○	○	○	○	Modern
Boring	○	○	○	○	○	○	○	Interesting
Inexpensive	○	○	○	○	○	○	○	Expensive
Dirty	○	○	○	○	○	○	○	Clean
Unreliable	○	○	○	○	○	○	○	Reliable

Hoe verschilt dit met semantic van klei soort waar ellen het mee vergeleek

Wat zijn volgens ellen de voordelen van 3d printen van keramiek?

Wat zijn de nadelen?

Zou ze zelf ooit geïnteresseerd zijn in het 3d printen van keramiek waarom wel/niet?

Appendix I: Tinkering diary

I Learning to print with the material and how to fire parts

I-1 first test printing with ceramic material

Purpose:
First time working with the ceramic material so the purpose of this test is to see how the material behaves while printing compared to the other normal Formlabs materials

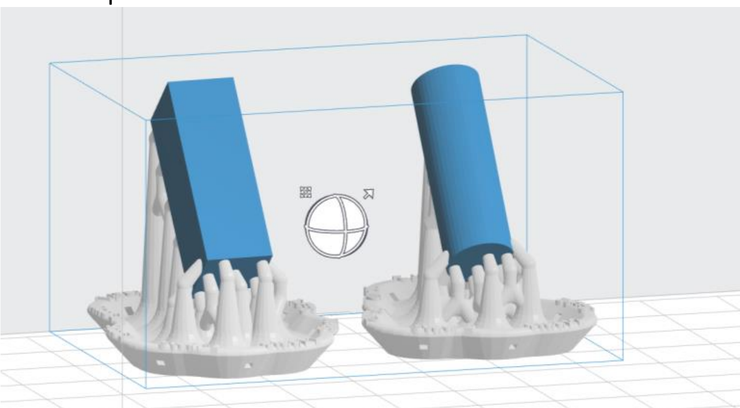
Date: 23-4-2019

Printing settings:

Support density	1,00
Support touch point size	1,40 mm
Printed in an angle	Yes
Ceramic Z-scale factor	1,12

Duration: ~ 3 hours

Test sample:



Results:

Model is printed in a wrong way. The top and bottom faces of the models are not perpendicular to the other faces anymore. This is caused by a combination of the build plate moving upwards, the resin tank moving sideways and printing the model in an angle.
Why is this not a problem for the other materials?

I-2 test print tensile braw bar

Purpose:
I want to execute tensile tests and I need drawbars for this test so I will print one to see if it will print successfully using the below shown settings and support. It is quite a difficult shape since it is thin and long so wire like. It will be printed in an angle since this way it is better supported compared to printing it vertically but it can be that it will print the wrong way like printing test 1.

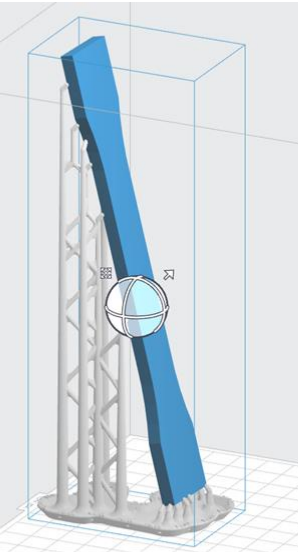
Date: 24-4-2019

Printing settings:

Support density	1,00
Support touch point size	1,40 mm
Printed in an angle	Yes
Ceramic Z-scale factor	1,12

Duration: ~ 10 hours

Test sample:



Results:

Model is printed in a wrong way again. So models should definitely not be printed in an angle anymore. Why is the support printed correctly but the model isn't? Is it because the model is placed in an angle and the support isn't? Printing a drawbar in a straight position now to test this.

Material is brittle so when printing high, thin wire like models it can happen that the model releases itself from the support and drops in the resin tank. Next test models will be printed horizontally and vertically to see if they will print without flaws and to see if the horizontally printed models will release themselves from the support or if this only happens for high wired like shapes.

I-3 second try printing tensile draw bar

Purpose:
Printing test 2 failed and I still need drawbars for my tensile testing. Since I now know for sure that models should not be printed in an angle I will be printing the models horizontally and vertically to see if the prints will succeed.

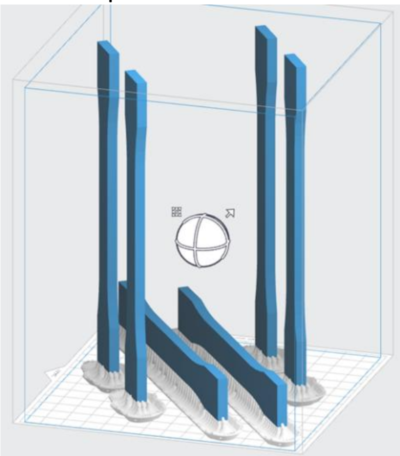
Date: 25-4-2019

Printing settings:

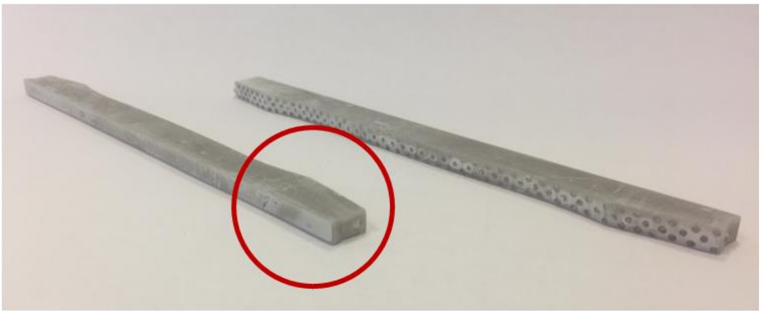
Support density	1,00
Support touch point size	1,40 mm
Printed in an angle	No, horizontally and vertically
Ceramic Z-scale factor	1,12

Duration: ~ 14 hours

Test sample:



Results:



- One horizontally and all vertically printed models released themselves from their support. The horizontally printed models were probably released from the support because the cross sectional area of the models was to excessive for the brittle support to hold. The part which was printed vertically also release itself from the support but here the cross sectional area was not too excessive so this probably failed because of Insufficient support.

- The vertically printed models did print correctly. The horizontally printed models did have flaws. It looks like it was not supported correctly and because of this the models show deflection at both ends.
- The three vertically printed parts which were still attached to their support had a prominent line. Formlabs explains that this can happen when a print is paused for a period of time and resumed again. The material gets the chance to dry and settle and this is why the line occurs.
- I was too eager to print 6 samples at ones and this was not smart. I actually was not experienced enough since both the previous prints failed. I have to slow down a bit and really get to know the do's and don’ts before I can print this many samples at ones.

I-4 Firing parts for the first time

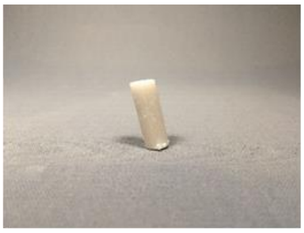
Purpose:
First time firing samples. Is to see what happens when a variety of shapes is baked. And also what the baked material looks like and how it feels.

Date: 25-4-2019

Firing schedule

Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	9	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**36,5**	

Test parts:

Results:





- *Cracks in layer direction*
  Possible causes: Burnout hold was too short and/or ramp rate of ramp 2 was too fast. Or something else like wall thickness too thick?
- *Shrinkage*
  Standard; parts will always shrink approx. 15% because of firing.
- *Sagging*

Tall support structure ended up sagging. This happened because the geometry is not self-supporting

- *Success*
  All small support parts were a success. No cracking, warping, sagging, slumping or anything else

I-5 Printing and firing impact test samples

Printing

Purpose:
Since printing drawbars so far failed I chose to print an easier shape namely specimen for impact testing. This part is less wire like and has a smaller cross sectional area. I increased the support touch points to 2,00 mm instead of 1,40 mm in the hope that the part will not release itself for the support anymore. Since I am still not sure this will work I will print one part instead of filling the build plate. I have positioned the part horizontally this way it has more support compared to printing it vertically. This does result in a bigger cross sectional area so maybe a higher support density or a bigger touch point size is needed. It is known if this is needed after the part is printed.

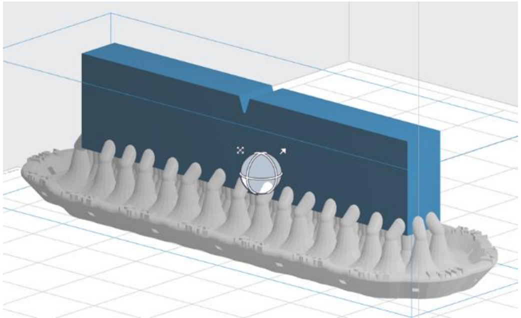
Date: 29-4-2019

Printing settings:

Support density	1,00
Support touch point size	2,00 mm
Printed in an angle	No, horizontally
Ceramic Z-scale factor	1,12

Duration: ~ 3 hours

Test sample:



Results:

The print succeeded. The part had sufficient support because the print was a success even with the bigger cross sectional area. So now I know that models printed with this material need support touch points of 2,00 mm.

Firing

Purpose:
Test what the best firing settings would be for the impact samples. The sample has a width of 7 mm so burnout hold time should be 7 hours according to the information given by Formlabs. Will increase the burnout hold time by 1.5 hour since a longer burnout hold will not harm the sample, but it will make sure that all the plastic is burned out so no cracks should occur.

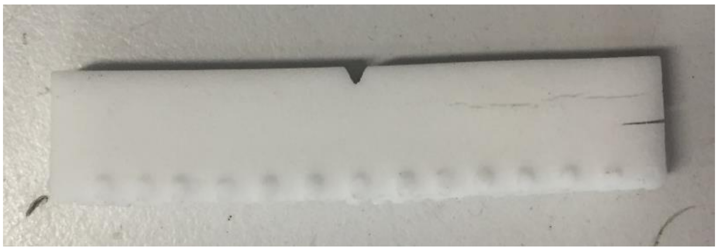
Date: 2-5-2019

Firing schedule

Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	9,5	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**37,0**	

Test sample:

Results:



Cracking still occurred even with a burnout hold of 9.5 hours. This means that burnout hold is still too short or samples should be printed with thinner wall thicknesses.

II Printing and firing technical test parts

II-1 Printing and firing samples for impact test

Printing

Purpose:
Now that I know which settings to use to succesfully print impact specimen I will print 2 at a time. I will use support touch points of 2,00 mm again and will print the parts horizontally again. The parts are duplicates so they have exactly the same support.

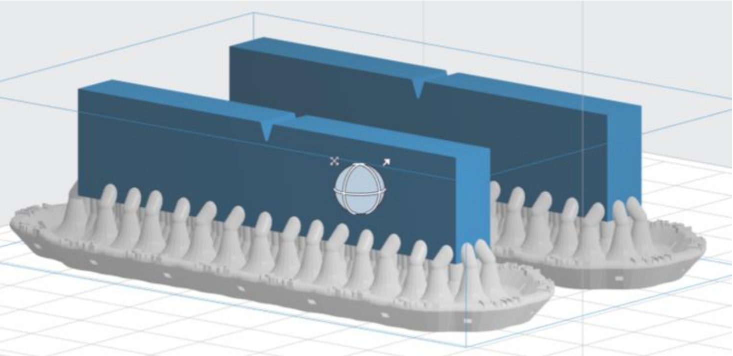
Date: 30-4-2019

Printing settings:

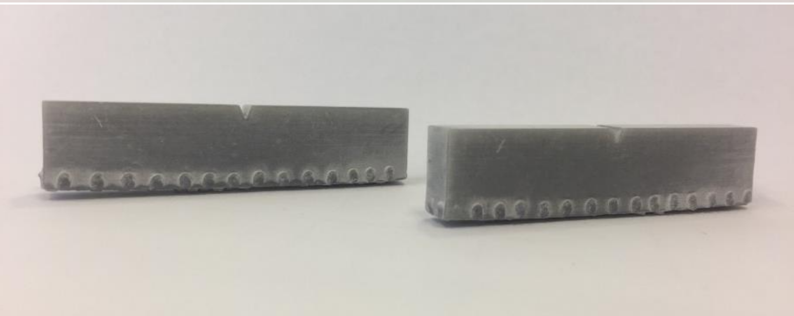
Support density	1,00
Support touch point size	2,00 mm
Printed in an angle	No, horizontally
Ceramic Z-scale factor	1,12

Duration: ~ 3,5 hours per print

Test sample:



Results:



Print 5 succeeded so I started print 6 which was identical and this one succeeded as well.

Firing

Purpose:

Test what the best baking settings would be for the impact samples. The sample has a width of 7 mm so burnout hold time should be 7 hours according to the information given by Formlabs. Burnout hold of 9,5 was not enough because cracking in the layer direction still occurred. Will increase the burnout hold time by 2 hours now instead of 1,5 to see if this has effect. So, burnout hold time will be 10 hours now and hopefully no cracks will occur.

Date: 6-5-2019

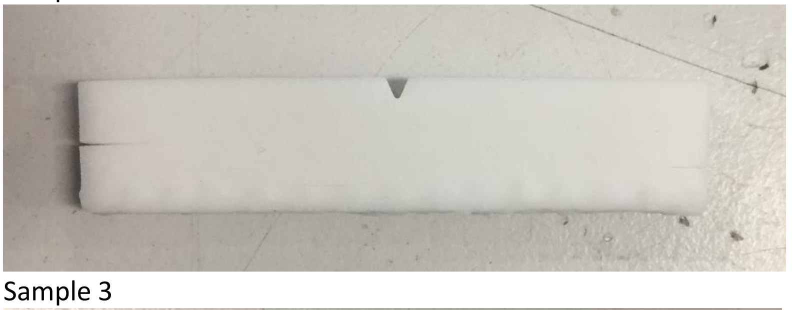
Firing schedule

Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	10	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**37,5**	

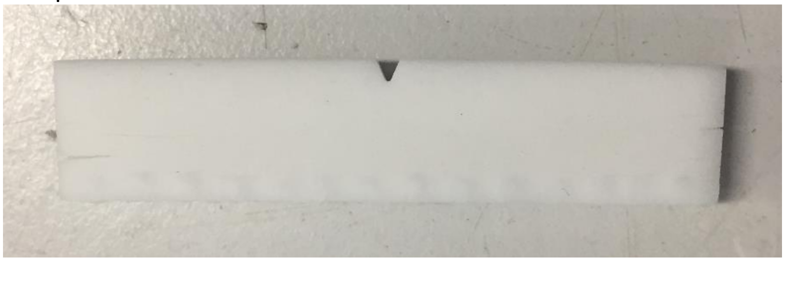
Test samples:

Results:

Sample 2



Sample 3



Cracking in the layer direction still occurred for both samples even with a burnout hold of 10 hours. The burnout hold cannot be longer than 10 hours since this is the limit of the kiln used. So, when wanting to produce samples without cracks the wall thickness of the samples should be thinner.

II-2 Printing and firing samples for tensile test

Printing

II-2.1 Trial 1

Purpose:
With the current updated printing settings it should be possible to print drawbars. So the purpose of this test is to successfully print a drawbar. I will start with printing one drawbar to see if the settings actually work for this sample. The part will be printed horizontally to make sure the part has enough support.

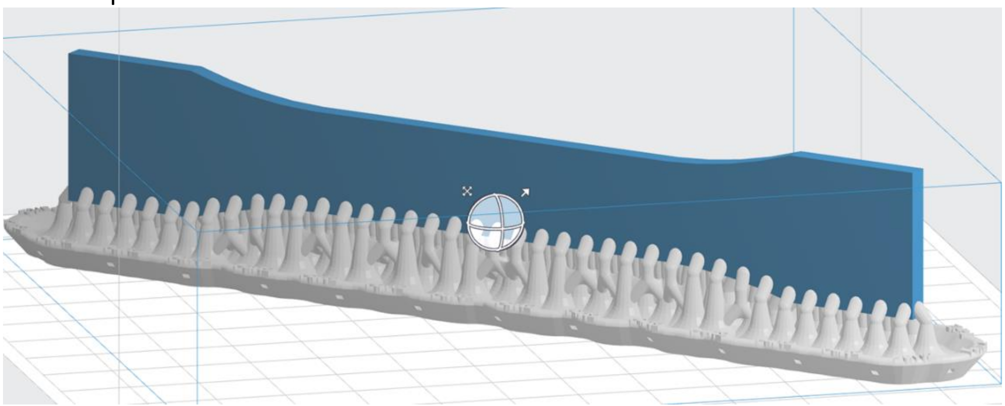
Date: 6-5-2019

Printing settings:

Support density	1,00
Support touch point size	2,00 mm
Printed in an angle	No, horizontally
Ceramic Z-scale factor	1,12

Duration: ~ 3,5 hours

Test sample:



Results:

The print was a success so now I know that it is possible to print drawbars with these settings.

II-2.2 Trial 2&3 in open mode

Purpose:

More drawbars are needed so more have to be printed. The material level left is low and this can cause problems with printing. To solve these problems the prints will be printed in open mode. The same printing settings and model as printing test II-2.1 are used.

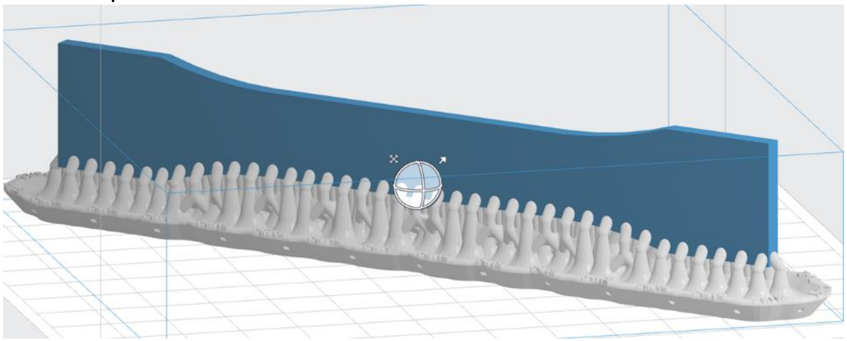
Date: 7-5-2019 & 9-5-2019

Printing settings:

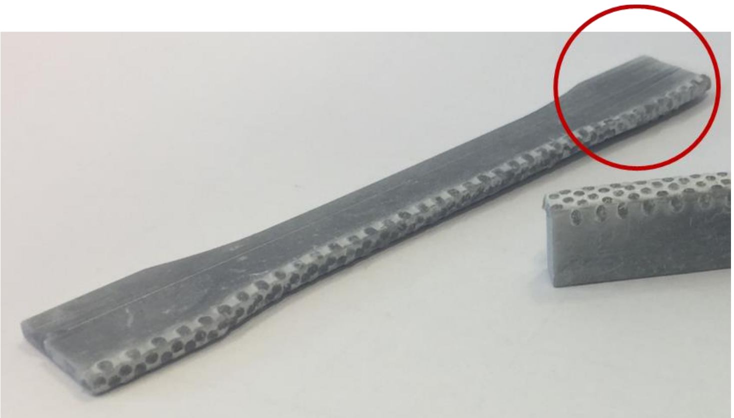
Support density	1,00
Support touch point size	2,00 mm
Printed in an angle	No, horizontally
Ceramic Z-scale factor	1,12

Duration: ~ 3,5 hours per print

Test sample:



Results:



Print 9 was a success. Print 10 started with an even lower level of resin in the tank. Both tests were printed in open mode but print 10 was printed with a part of support missing due to low resin levels and bad spreading. This resulted in deformation at one of the ends of the drawbar. This was no problem since this part of the drawbar would be clamped in.

II-2.3 Printing tensile draw bars

Purpose:

More drawbars are needed so more have to be printed. New material arrived so now it is possible to print 2 drawbars at a time. The same printing settings and model as printing test II-2.1 and II-2.2 are used. The parts are duplicates so they have exactly the same support.

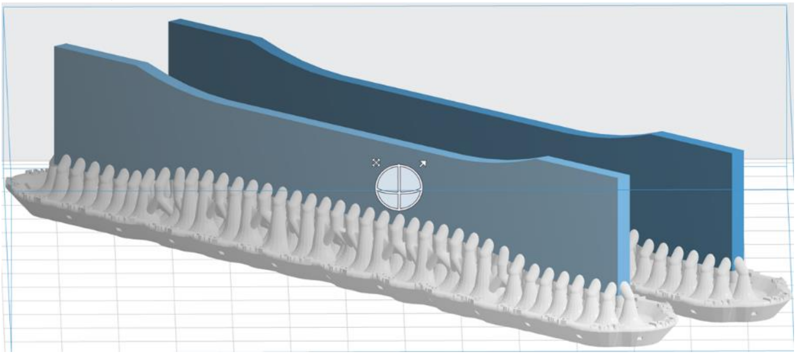
Date: 13-5-2019 & 14-5-2019

Printing settings:

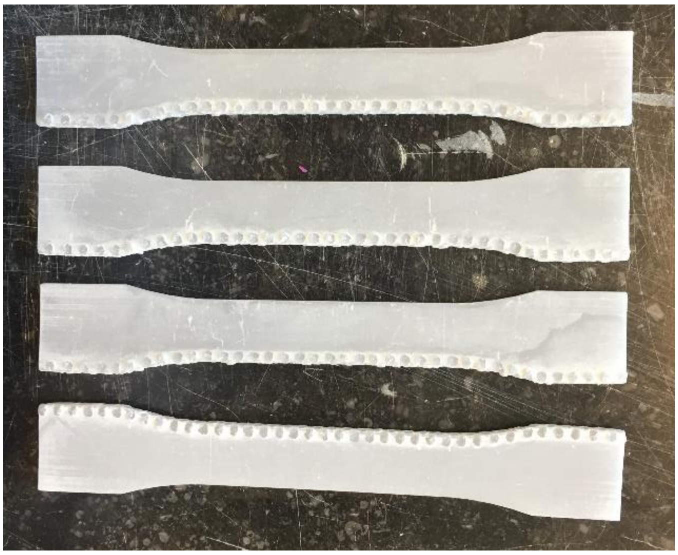
Support density	1,00
Support touch point size	2,00 mm
Printed in an angle	No, horizontally
Ceramic Z-scale factor	1,12

Duration: ~ 4,5 hours per print

Test sample:



Results:



Both prints succeeded.

II-2.4 Firing failed tensile draw bar

Purpose:
Test what the best baking settings would be for the tensile samples. The sample has a width of 5 mm so burnout hold time should be 5 hours according to the information given by Formlabs. A sample with a similar thickness was fired with a burnout hold time of 9 hours and it still cracked (I-4). This was a failed print with a weird geometry so this can also be the reason it cracked. For this sample I will increase the burnout hold time by 3 hours and make it a total of 8 hours instead of 9 since this sample has a more normal geometry. Hopefully 8 hours will make sure that all the plastic is burned out so no cracks occur.

Date: 9-5-2019

Firing schedule

Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	8	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**35,5**	

Test sample:

Results:

No cracks occurred but a slight warping is visible.

II-2.5 Firing tensile draw bars

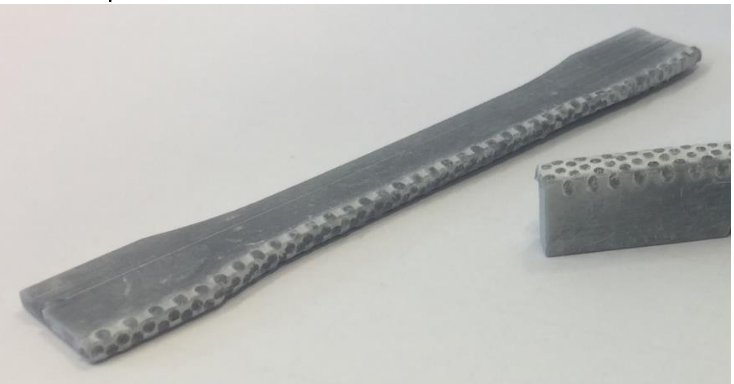
Purpose:
Test what the best baking settings would be for the tensile samples. The sample has a width of 3 mm so burnout hold time should be 3 hours according to the information given by Formlabs. The previous tensile sample had a thickness of 5 mm and was fired with a burn out hold time of 8 hours and no cracks occurred. This sample is slightly thinner so it will be fired with a burnout hold time of 7 hours. Hopefully 7 hours will make sure that all the plastic is burned out so no cracks occur.

Date: 13-5-2019

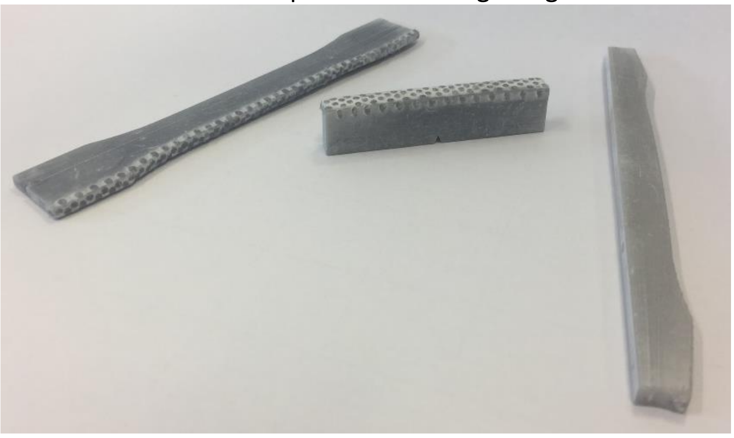
Firing schedule

Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	7	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**34,5**	

Test sample:



The previous sample (II-2.4) did have a different colour. It looked like it was dryer compared to these samples and samples which were put into the kiln before. This colour difference/dryness may also have effect of if the sample cracks during firing or not. This should/can be tested.



Results:


Success for all three samples because no cracks visible so it can also be concluded that if the samples were still slightly wet (darker colour) it did not have an effect on the firing process since the samples did not crack.

The samples had some slight warping. Formlabs (2019) mentions that this is probably caused by setter drag and solved by putting kiln wash on the shelf. Kiln wash was already put on shelf and it still warped so what caused this than?

II-3 Printing and firing samples for 3 point bending test

Printing

Purpose:
It was not possible to execute the tensile test with the fired tensile draw bars since they were to brittle. They could not be clamped into the machine because they would break. Because of this a 3 point bending test will be executed instead. The build plate will be filled will samples since I am confident enough about how to print with the material now. The parts are duplicates so they have exactly the same support.

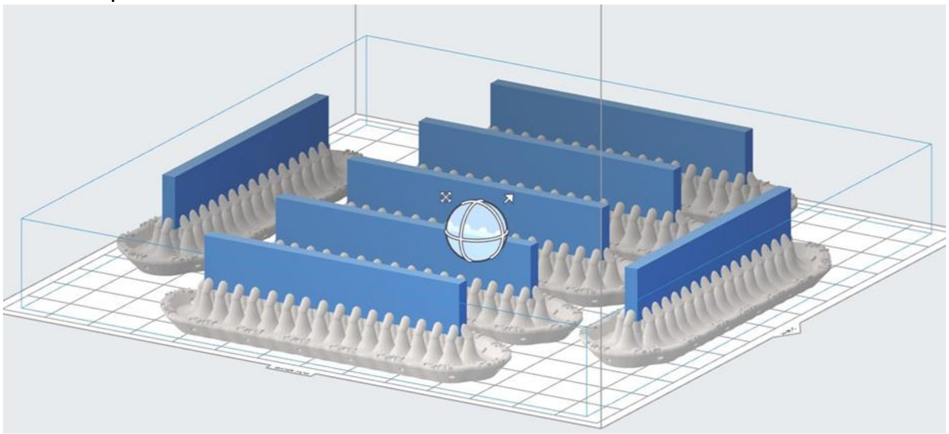
Date: 16-5-2019

Printing settings:

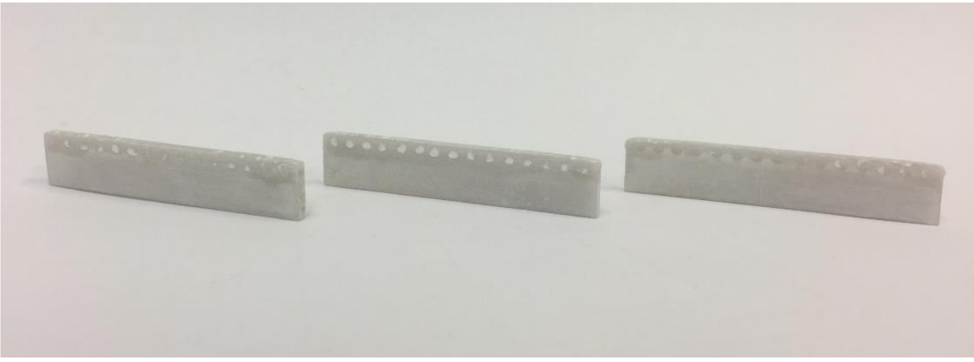
Support density	1,00
Support touch point size	2,00 mm
Printed in an angle	No, horizontally
Ceramic Z-scale factor	1,12

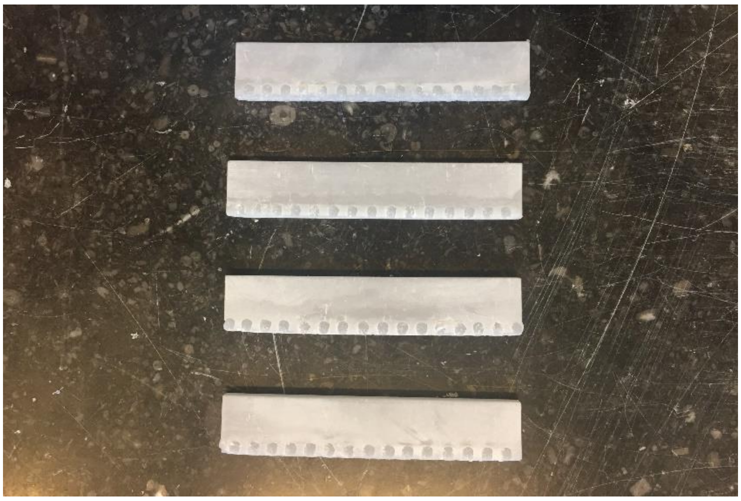
Duration: ~ 4,5 hours

Test sample:



Results:





All samples were printed successfully without deformations. So, it is now certain that it is possible to print multiple samples at a time with the current settings.

Firing

Purpose:

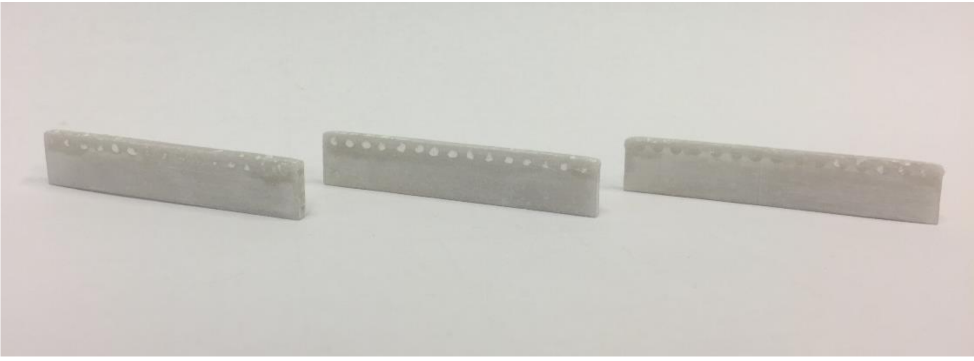
The samples printed had to be fired to be able to execute the 3 point bending test. The samples have a thickness of 3 mm so need a burnout hold time of at least 7 hours (II-2.5). It is fired together with samples which have a wall thickness thicker than 3 mm (IV-1.2 and V-4.2) so the burnout hold time will be set to 8 hours.

Date: 20-5-2019

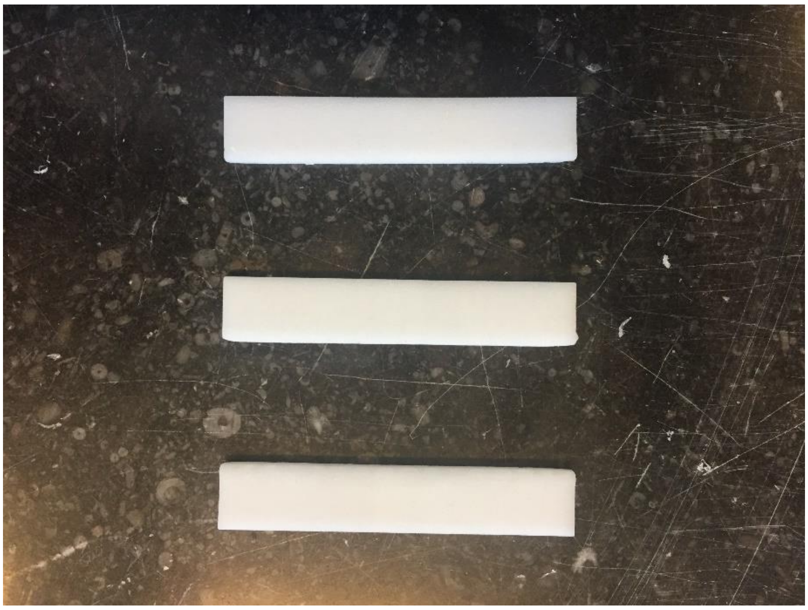
Firing schedule

Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	8	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**35,5**	

Test sample:



Results:



The firing was a success. The samples came out of the kiln without any cracks and with very slight warping.

II-4 Printing and firing samples for heat resistance test

Printing

Purpose:
heat

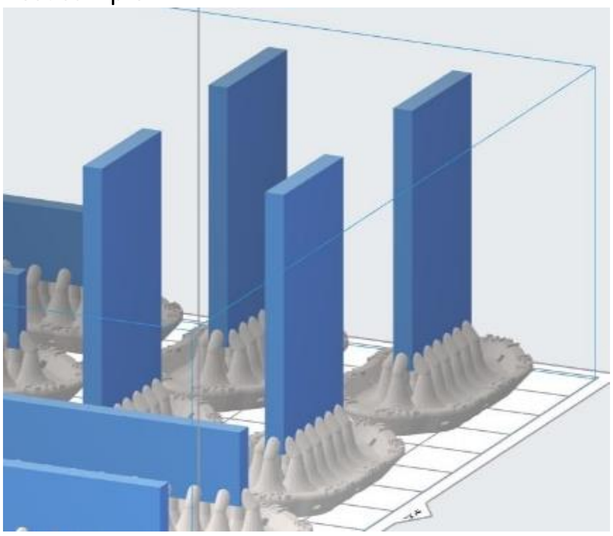
Date: 10-6-2019

Printing settings:

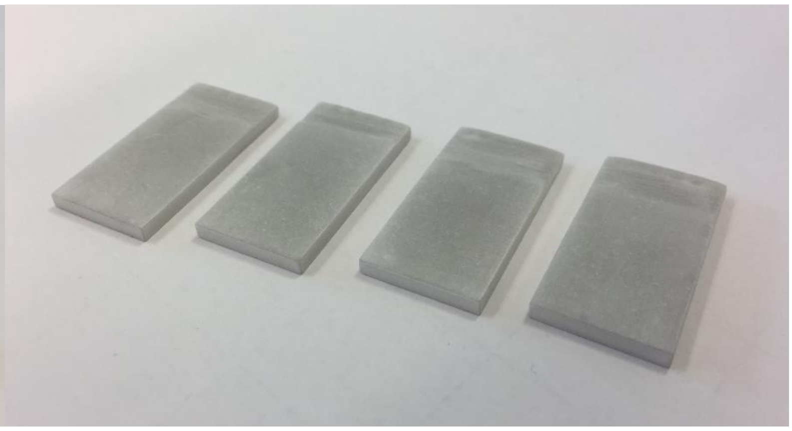
Support density	1,00
Support touch point size	2,00 mm
Printed in an angle	No, vertically
Ceramic Z-scale factor	1,12

Duration: ~ 6 hours

Test sample:



Results:

Print was successful

Firing

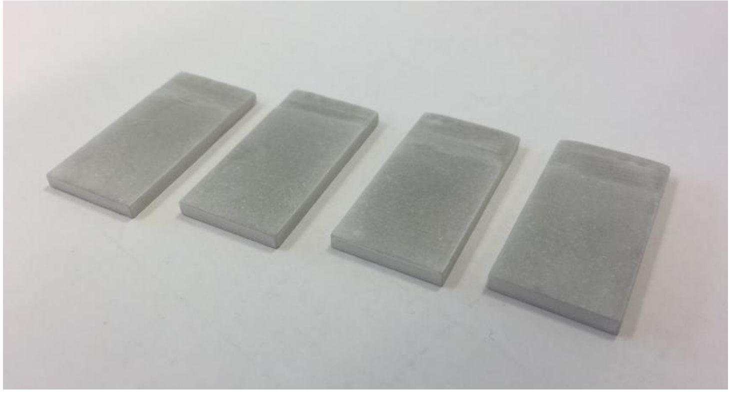
Purpose:
Fired together with VII-2.1

Date: 14-6-2019

Firing schedule

Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	8	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**35,5**	

Test sample:



Results:

Samples fired without warping or cracking

Heat resistance procedure

Unfortunately there was not enough time to test the heat resistance of the material so this should be done in future research.

II-5 Printing and firing samples for solar radiation test

Printing

Purpose:
Solar radiation

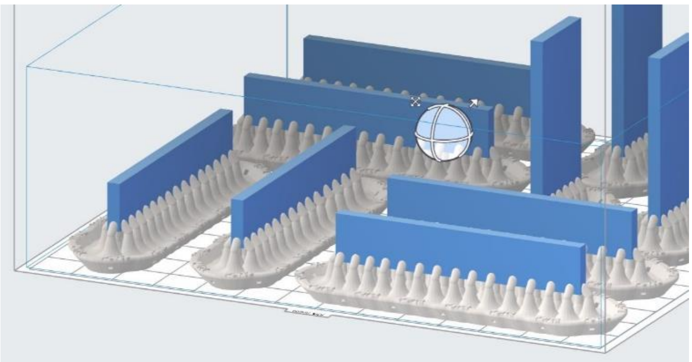
Date: 10-6-2019 & 11-6-2019

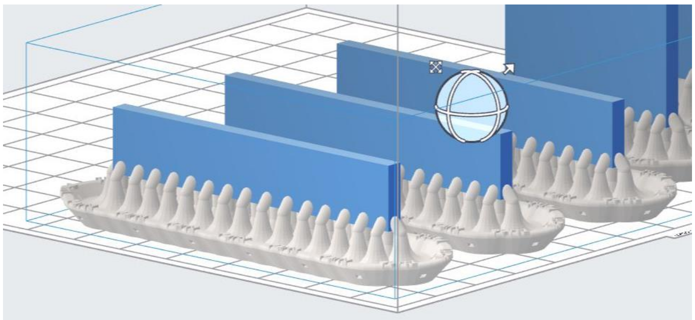
Printing settings:

Support density	1,00
Support touch point size	2,00 mm
Printed in an angle	No, horizontally
Ceramic Z-scale factor	1,12

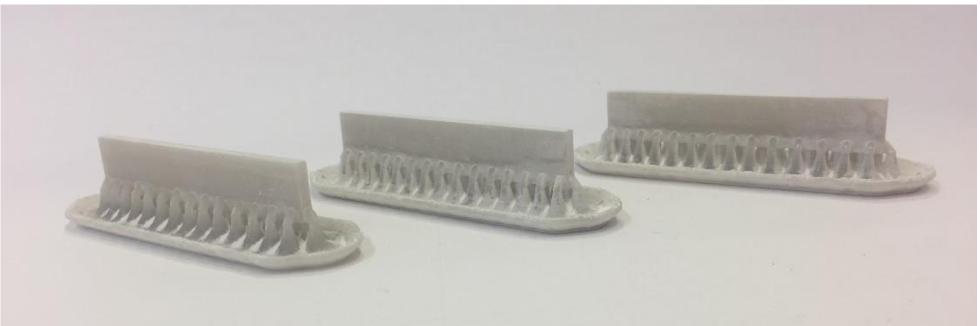
Duration: ~ 10 hours

Test sample:





Results:



Print was successful

Solar radiation procedure

Goal: To see if the properties of the part change when it is exposed to UV radiation after the printing process. Could happen when a part is left outside in the sun after printing.

UV C: 100 to 280 nm, invisible to human eye, Due to absorption by the atmosphere very little reaches Earth's surface
UV B: 280 to 315 nm, invisible to human eye, also greatly absorbed by the Earth's atmosphere, directly damages DNA and causes sunburn
UV A: 315 to 400 nm, 380 to 400 nm is visible to human eye, damages DNA via indirect routes and can cause cancer

Form cure: 405 nm, visible to human eye, has even exposure through well-balanced light placement and a rotating turntable, uses heat to speed up the curing process

Mimicking solar radiation for one day using Form cure. Part is now only exposed to UV A not B and C but this should not be a problem because photopolymers inside the Formlabs resin activate at higher frequencies, so only UV A. Outside, part would be exposed to sun light and general Dutch weather conditions. Dutch weather conditions should also be mimicked since these do effect the curing process. Warmer weather will speed up the process. The Form cure has a minimum temperature of 35 °C.
Room temperature is 21 °C. The average temperature in the Netherlands is 10.5 °C. The average hours of sun a day in the Netherland is 4.5 hours. The average temperature during the months June - August in the Netherlands is 18 °C. The average hours of sun during the months June - August in the Netherlands is 6.6 hours a day. The average temperature during the months December - February in the Netherlands is 3.4 °C. The average hours of sun during the months December - February in the Netherlands is 2.1 hours a day.

A summer day will be mimicked for this research so the temperature of the Form cure will be shut off.
So, 3 samples will be placed inside the Form cure for 2.1 hours (130 min) at 405 nm (UV A) at a temperature of 21 °C.
3 samples will be placed inside the Form cure for 4.5 hours (270 min) at 405 nm (UV A) at a temperature of 21 °C.
3 samples will be placed inside the Form cure for 6.6 hours (400 min) at 405 nm (UV A) at a temperature of 21 °C.

Results
After taking the samples out of the curer no difference was seen. Unfortunately there was not enough time to execute 3 point bending tests to test property differences.

II-6 Printing and firing samples for burnout hold test

Purpose:
The purpose of this test was to see what a sample actually look like when taking it out of the kiln before ramp 2 and before the sample is sintered. This way understanding can be made about what sintering actually is and what the surface texture of a sample looks like when not sintered and when sintered.

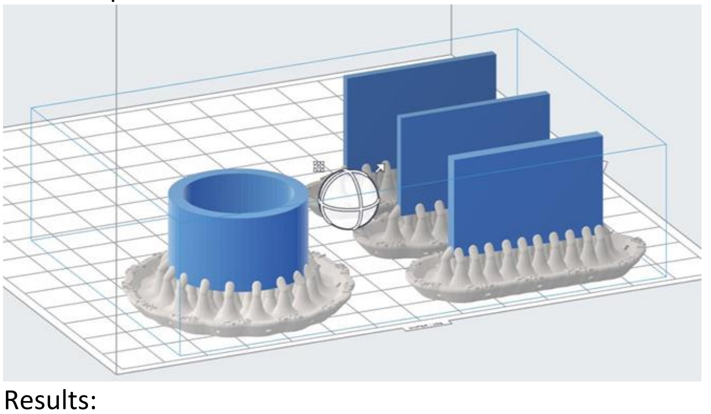
Date: 28-5-2019

Printing settings:

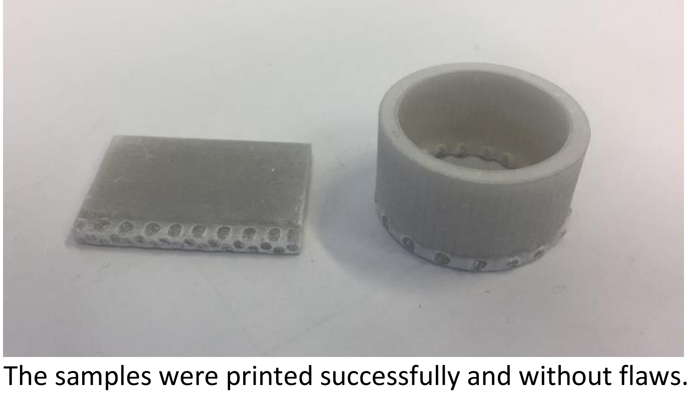
Support density	1,00
Support touch point size	2,00 mm
Printed in an angle	No, horizontally and vertically
Ceramic Z-scale factor	1,12

Duration: ~ 3,5 hours

Test sample:



Results:



The samples were printed successfully and without flaws.

The kiln broke so it was not possible to fire these parts anymore. So, it is not clear what the state of a sample will be when taking it out of the oven before sintering.

III Testing shape limitations

III-1 Printing a thin walled high shape

Purpose:
After having successfully printed the impact specimen I wanted to see if with the now known settings I was able to print higher parts with thin walls. So I decided to print a square with a wall thickness of 1,90 mm.

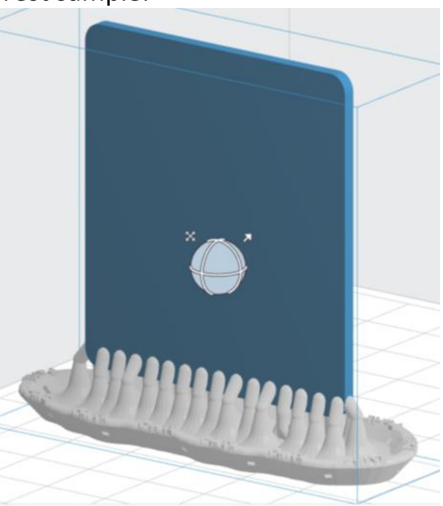
Date: 1-5-2019

Printing settings:

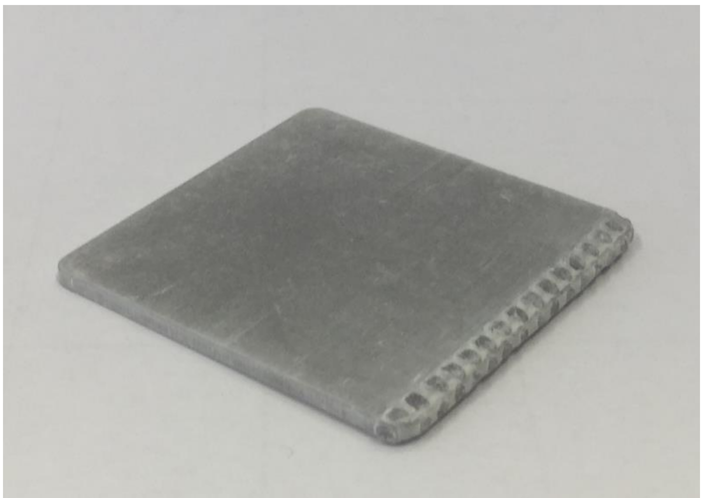
Support density	1,00
Support touch point size	2,00 mm
Printed in an angle	No, vertically
Ceramic Z-scale factor	1,12

Duration: ~ 4,5 hours

Test sample:



Results:



The print was a success so now I am more confident that it is possible to print drawbars with these settings.

III-2 Printing and firing high wire like shapes

Printing

Purpose:
To research how beams/wires which are not self-supporting move when fired in a kiln. Part is printed twice to see if they always bent/sag the same way during firing or if this changes. The parts are duplicates so they are identical. This part was personally modelled in SolidWorks with a similar looking support structure as is normally generated by PreForm and printed directly onto the build platform. This can of course cause problems since the support is now not generated by PreForm.

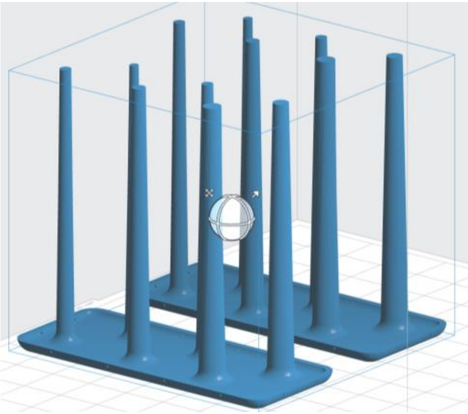
Date: 14-5-2019

Printing settings:

Support density	Personally modelled
Support touch point size	Personally modelled
Printed in an angle	No, vertically
Ceramic Z-scale factor	Personally modelled

Duration: ~ 5 hours

Test sample:



Results:

Print succeeded and no problems occured eventhough the support structured was personally created in SolidWorks and not generated by PreForm.

Firing

Purpose:

Test how parts, which are not self-supporting, sag due to firing. The sample has a variety of thicknesses and the thickest wall thickness is 6 mm so according to Formlabs the burnout hold time should be 6 hours. However parts with a wall thickness of 7 mm were previously fired with a burnout hold of 10 hours to prevent cracks. For those parts the walls did not vary in thickness and the complete model was 7 mm. For this model only a small part has a thickness of 6 mm most of it is thinner and previous parts with a wall thickness of 5 mm have been fired with a burnout hold time of 8 hours and no cracks occurred. So, this model will be fired with a burnout hold of 8 hours. Hopefully 8 hours will make sure that all the plastic is burned out so no cracks occur. These samples will be fired together with III-3 and V-4.1.

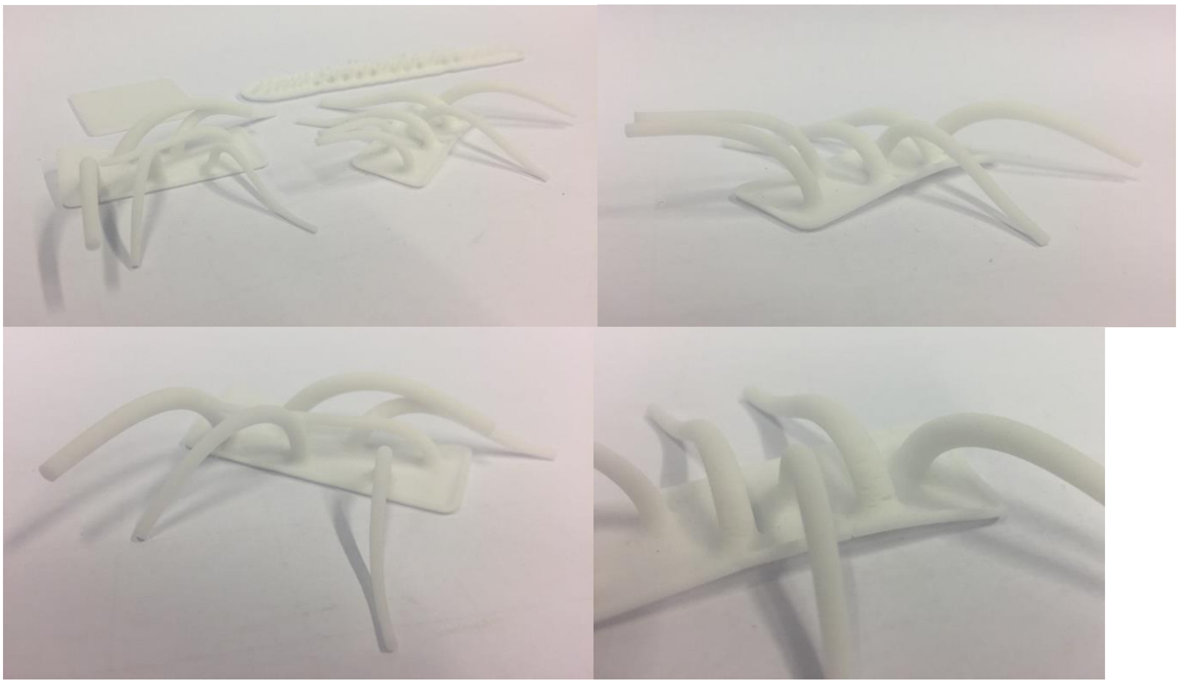
Date: 16-5-2019

Firing schedule

Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	8	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**35,5**	

Test samples:


Results:



The samples have wire like shapes. These wire like shapes are not self-supporting and sag during firing. Even the thicker wires sag but they do sag less. Especially at the end. The thinner wires sag and deform from the bottom to the top but the thicker wires sag mostly at the bottom close to the base plate. All wires have deep cracks because of the far deformation. It looks like the material is not made for this type of deformations and that the layers split when bending this far, creating the cracks. The cracks are in the direction of the layers.
Both samples have the same wire dimensions but they did not sag the same way so the sagging is not consistent and cannot be predicted.

III-3 Measure the shrinkage of a fired sample

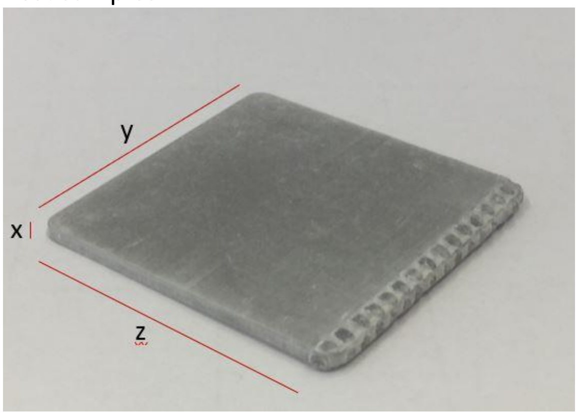
Purpose:
Together with the samples from III-2 and V-4.1 a sample (III-1) will be fired which will be measured before and after firing to be able to measure the shrinkage. This sample is thinner that the sagging sample (III-2) so the kiln setting will be fine.

Date: 16-5-2019

Firing schedule

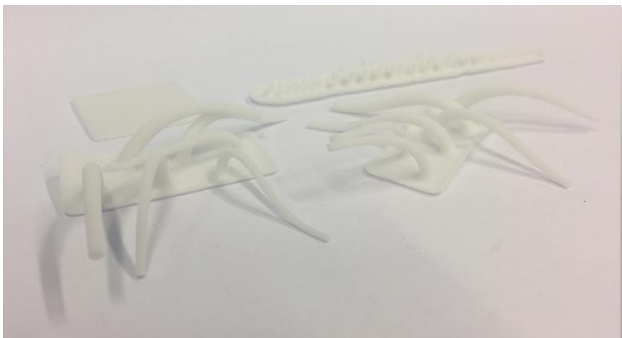
Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	8	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**35,5**	

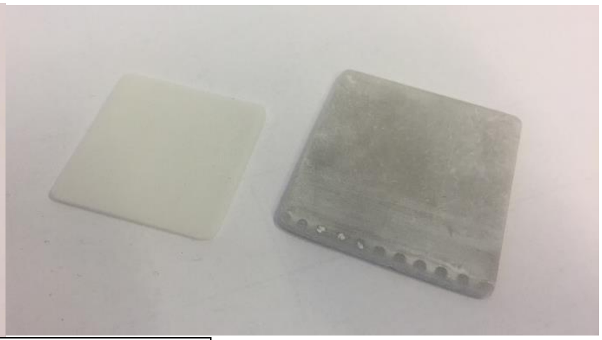
Test samples:



Thickness (x) 1,88 mm
Length (z) 45,32 mm
Width (y) 44,85 mm

Results:





Thickness (x)	1,70	9,6% shrinkage
Length (z)	37,36	17,6% shrinkage
Width (y)	39,00	13,0% shrinkage

The sample shrinks the most in the z direction as was mentioned by Formlabs in printing guide.

IV Controlled cracking 2D

IV-1 Trial 1

IV-1.1 Confirm if controlled cracking is possible

Purpose:
Read on the Formlabs website that prominent lines caused by resin settling during a long pause mid-print can crack during firing. During a failed print (I-3) this happened to three samples so I want to see if a crack actually occurs and what this looks like and if it can be manipulated and influenced. The samples have a wall thickness of approximately 6 mm. So, when following the guide from Formlabs, the burnout hold time should be 6 hours. It was heightened a bit to be sure that all the plastic would be burned out.

Date: 29-4-2019

Firing schedule

Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	6,5	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**34,0**	

Test samples:

Results:
Clear deep crack where prominent line was showing before firing.

Also cracks on other locations in direction of the layers. So burnout hold not long enough or wall thickness to thick.

The samples had some slight warping. Formlabs (2019) mentions that this is probably caused by setter drag and solved by putting kiln wash on the shelf. Kiln wash was already put on shelf and it still warped so what caused this than?

IV-1.2 Find optimal firing settings

Purpose:
It is confirmed that controlled cracking is possible. During the previous firing process the samples still had cracks on other locations in the direction of the layers. This could have been because of a too short burnout hold time or because of a too thick wall thickness. During this firing process the burnout hold time is set to 8 hours so it is longer. If the unintended cracks are still present after firing with this burnout hold time, the wall thickness should be made thinner for following samples. The sample are fired together with II-3 and V-4.2.

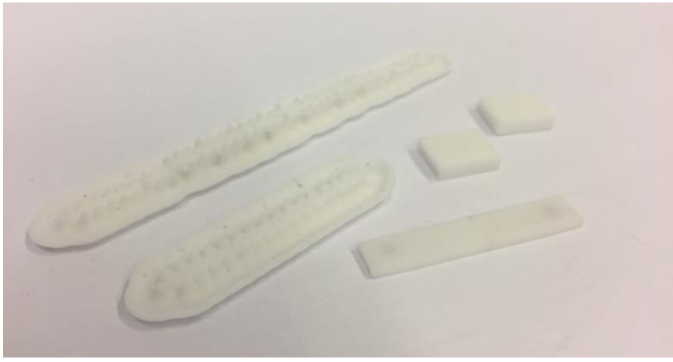
Date: 20-5-2019

Firing schedule

Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	8	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**35,5**	

Test sample:

Results:



Both samples again had clear deep cracks where the prominent lines were showing.
The samples also had cracks on other locations in the direction of the layers, even with the longer burnout hold time. So, this means that the samples should have thinner walls to be able to create samples without unintended cracks in the direction of the layers.
Both samples had no warping.

IV-2 Trial 2

IV-2.1 Failed controlled cracking

Purpose:
Printing test 3 had as a result a part with a very prominent line caused by pausing the print and resuming it again after some time. When firing a part with a prominent line a crack occurs at this spot. I find this interesting and want to play with this more. So, during this test 4 parts will be paused 3 times during printing and the duration of each pause will be different. I will test if the pause duration will have effect on how prominent the line will be. Furthermore I want to know if for each pause duration a crack occurs, when the part is fired, and if they differ. First the part will be paused for 5 min, afterwards 10 min and lastly for 20 min. 4 identical samples will be printed. 3 will be fired and one will not.

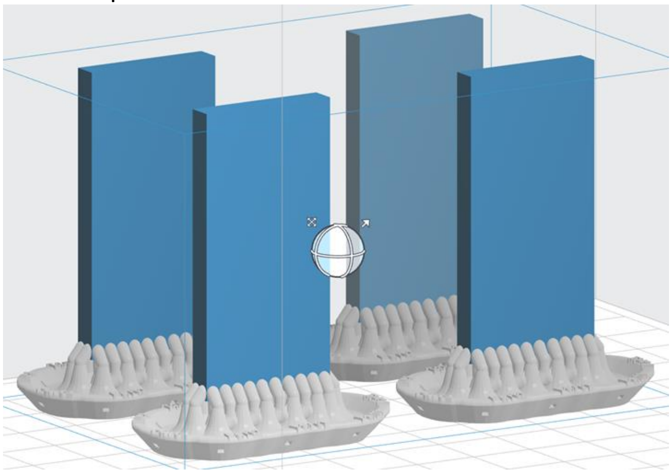
Date: 20-5-2019

Printing settings:

Support density	1,00
Support touch point size	2,00 mm
Printed in an angle	No, vertically
Ceramic Z-scale factor	1,12

Duration: ~ 5 hours

Test sample:



Results:

Print failed. The support of all 4 parts released themselves from the build plate. This is caused because the build plate was not rough enough. So it should be sanded better.

IV-2.2 Controlled cracking 2D

Printing

Purpose:
Executing the controlled cracking test (IV-2.1) again. 4 parts will be paused 3 times during printing and the duration of each pause will be different. The print will be paused for 5 minutes, 10 minutes and 20 minutes. Test if the pause duration will have effect on how prominent the line will be. Furthermore find out if for each pause duration a crack occurs, when the part is fired, and if they differ.

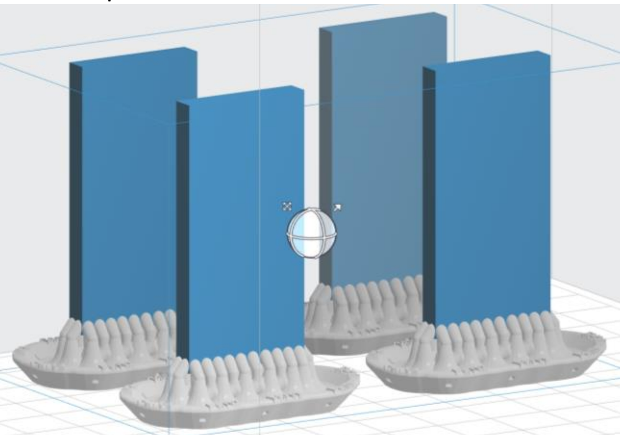
Date: 21-5-2019

Printing settings:

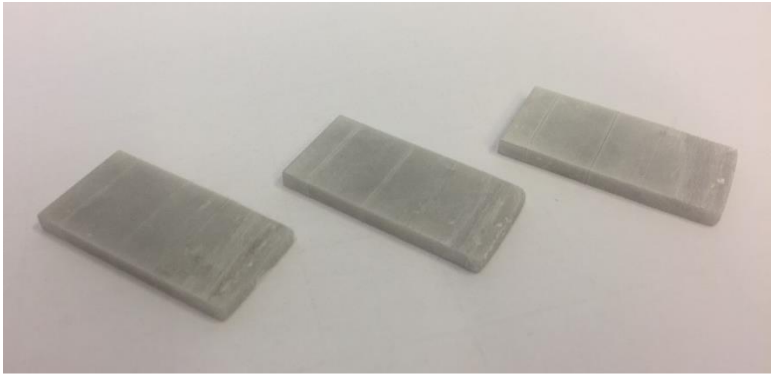
Support density	1,00
Support touch point size	2,00 mm
Printed in an angle	No, vertically
Ceramic Z-scale factor	1,12

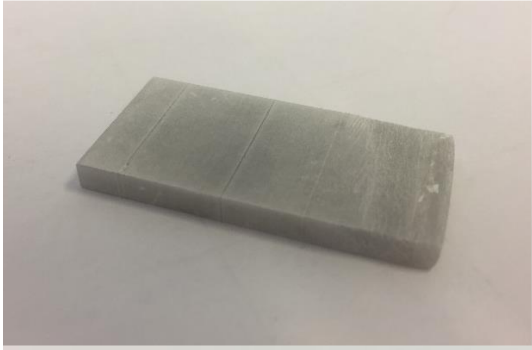
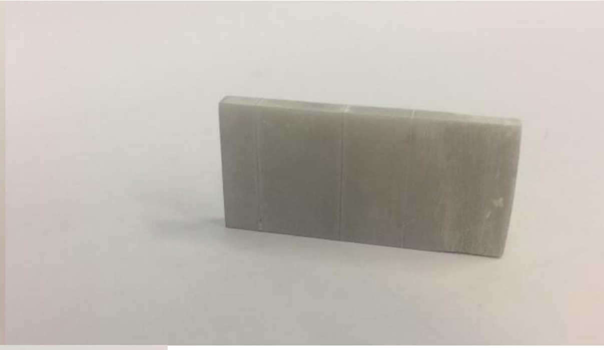
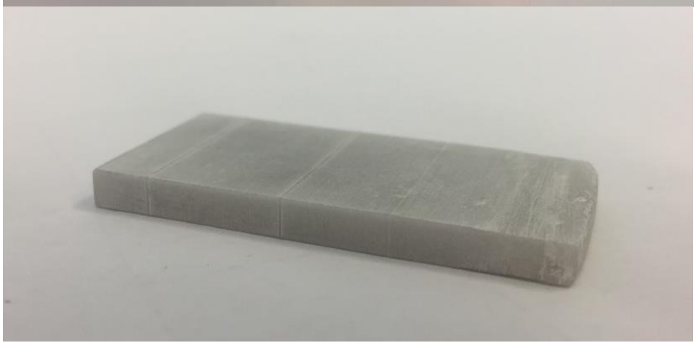
Duration: ~ 5 hours

Test sample:



Results:



Print was a success. A difference can be seen in how prominent the lines are so pause duration has effect on this.

Firing

Purpose:
The controlled cracks are created by resin settling during a pause mid print. Since the controlled cracking samples tested so far were actually failed prints, it is unknown how long they were actually paused during the printing process. So, to test if the pausing time actually has influence, 4 parts will be paused 3 times during printing and the duration of each pause will be different. 4 identical samples will be printed. 3 will be fired and one will not. First the part will be paused for 5 min, afterwards 10 min and lastly for 20 min. It will be tested if the pause duration will have effect on how prominent the line will be. Furthermore, it will become clear if for each pause duration a crack occurs, when the part is fired, and if they differ. The samples are fired together with V-1, V-2 and VI. A burnout hold time of 8 hours is used because the sampled have a thickness of 4 mm. Samples V-1, V-2 and VI are all thinner so this burnout hold time will work fine for these samples as well.

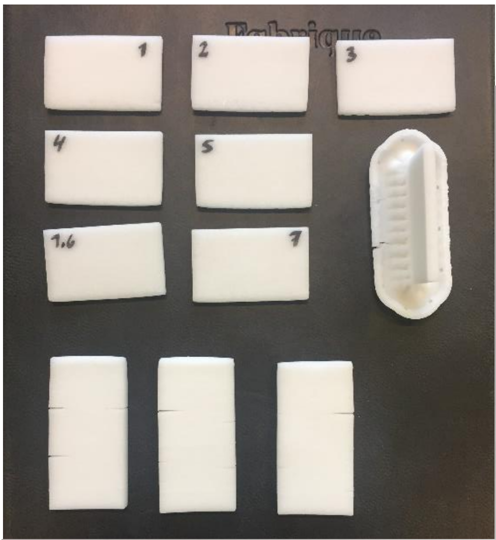
Date: 23-5-2019

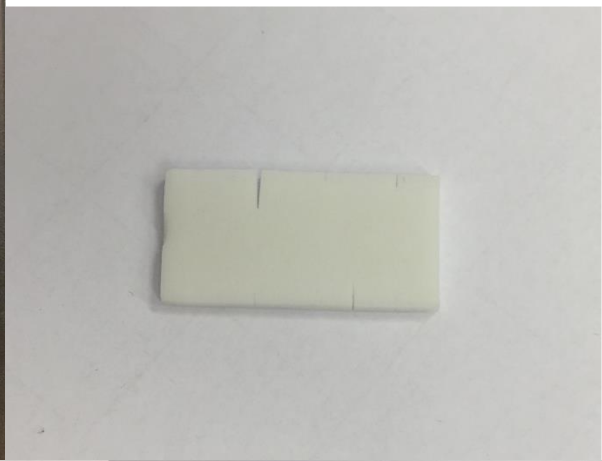
Firing schedule

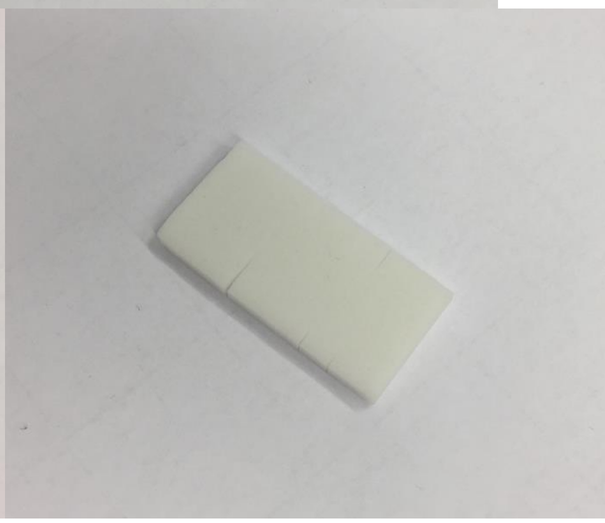
Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	8	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**35,5**	

Test sample:

Results:







All samples have controlled cracks. A difference can be seen in how prominent the cracks are so pause duration has effect on this. The 5 min pause creates the deepest cracks. The 10 minute pause creates more shallow cracks and the 20 minute pause does not create cracks only a visible line.

All samples also have cracks on other locations even with a burnout hold of 8 hours and a sample thickness of 4 mm. This means that the wall thickness of the samples is still too thick. This material is better fit for the production of very thin walled samples of < 3 mm.

V Influencing surface texture

V-1 Soaking in alcohol dry

Printing

Purpose:
The purpose of this test is to see if leaving the samples in alcohol for different amounts of time before firing has effect on the characteristics of the material. 5 samples with a thickness of 2.5 mm are printed. They will be cleaned and left in the alcohol for different amounts of time. All samples will get at least 24 hours to dry after soaking in the alcohol. Making sure that they are fired when dry.

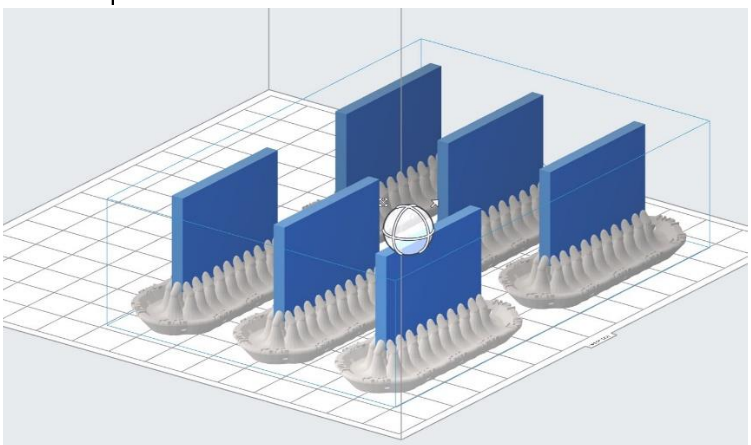
Date: 20-5-2019

Printing settings:

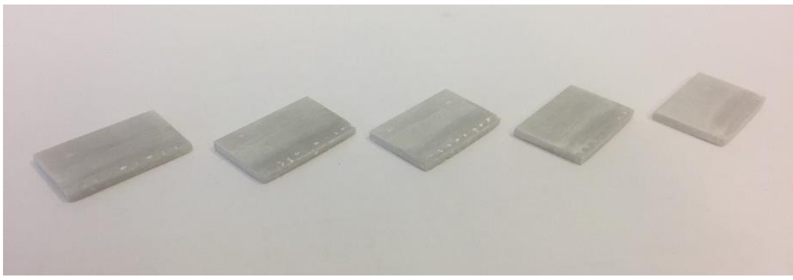
Support density	1,00
Support touch point size	2,00 mm
Printed in an angle	No, horizontally
Ceramic Z-scale factor	1,12

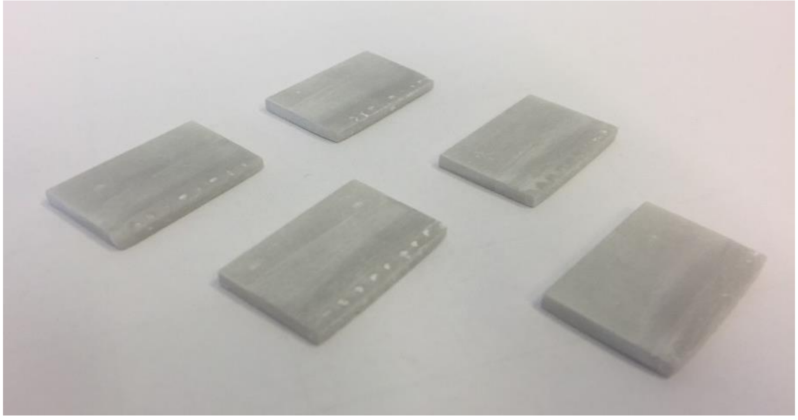
Duration: ~ 4 hours

Test sample:



Results:




All samples printed successfully without flaws or deformations.

Alcohol procedure

During the normal printing process, all samples are cleaned after printing and will not be kept in the alcohol basin for longer than 5 minutes. This is because the samples will soak up the alcohol when kept in the basin for longer and it will take longer to let them dry. For this test the sample will be kept in the alcohol basin for longer periods of time. 5 samples will be used for the test and these are the amounts of time they will be left in the basin.
Sample 1: 10 minutes
Sample 2: 30 minutes
Sample 3: 1 hour
Sample 4: 2 hours
Sample 5: 24 hours

All samples will at least be left to dry for one day (24 hours) before firing them to make sure they are not wet when put in the kiln. The drying time every sample has is:
Sample 1: 2 days (48 hours)
Sample 2: 2 days (47.5 hours)
Sample 3: 2 days (47 hours)
Sample 4: 2 days (46 hours)
Sample 5: 1 day (24 hours)

Firing

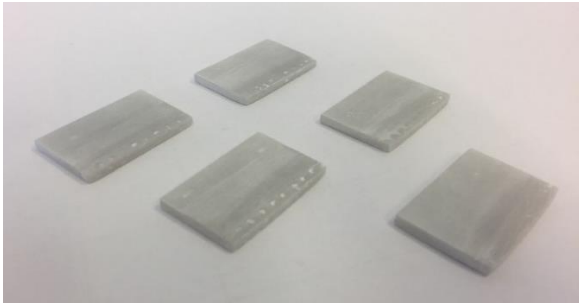
Purpose:
The samples are fired after having dried for at least one day. This is to see if the alcohol has effect on the characteristics of the samples. It could have effect on the vitrification so how porous or glass like the samples will be. The samples are fired together with IV-2.2, V-2 and VI. A burnout hold time of 8 hours is used because samples IV-2.2 have a thickness of 4 mm. These samples and samples V-2 and VI are all thinner so this burnout hold time will work fine for these samples as well.

Date: 23-5-2019

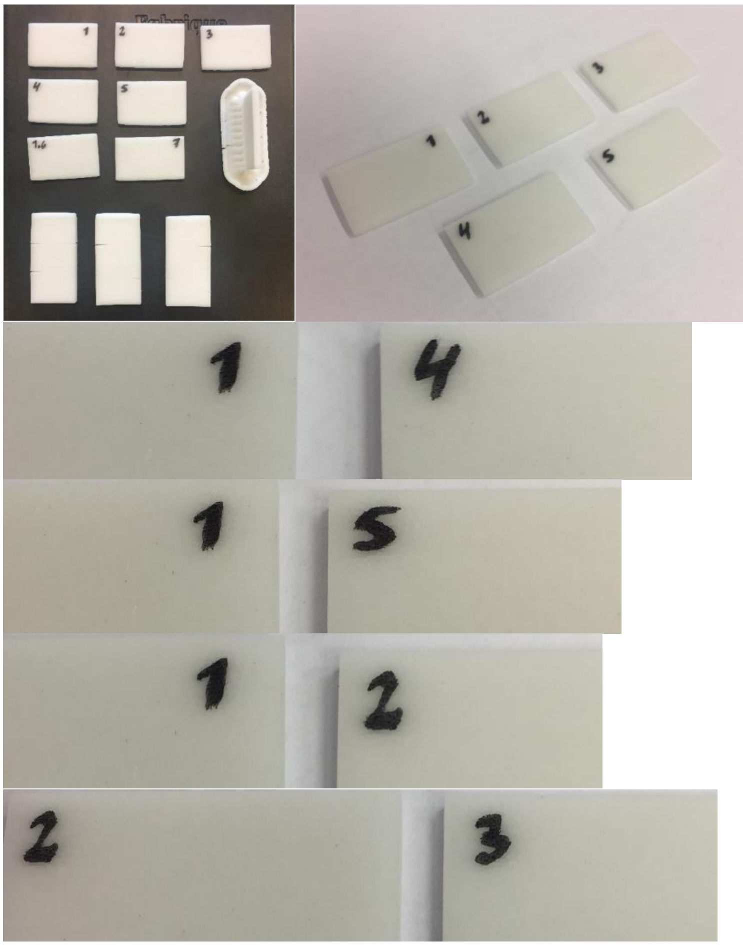
Firing schedule

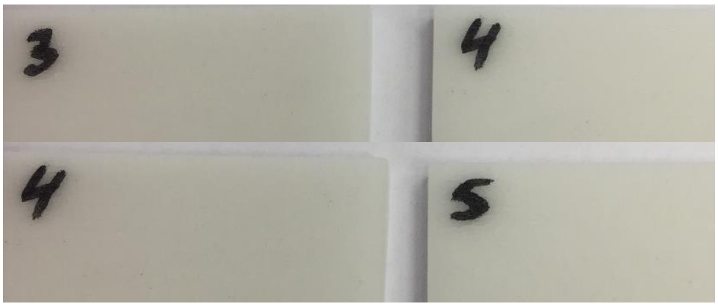
Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	8	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**35,5**	

Test sample:



Results:





A difference can be seen between the surface textures of the samples. Mostly between samples 1 and 5. Sample 1 looks more vitrified than sample 5 since it has a smoother surface without visible surface cracks. Sample 5 has a visible surface texture with small scale like cracks in the surface. There is no clear difference between samples 1, 2 and 3. Sample 4 is also more porous than sample 1 and has a rougher surface texture with visible cracks.

So, the alcohol does have an effect on the surface texture of the samples and does influence the vitrification process. But only when it has been soaked in the alcohol for at least 2 hours.

V-2 Soaking in alcohol wet

Printing

Purpose:
The purpose of this test is to fire samples which are not dried after cleaning. Two samples with a thickness of 2.5 mm were printed and left in the alcohol basin for different amounts of time.

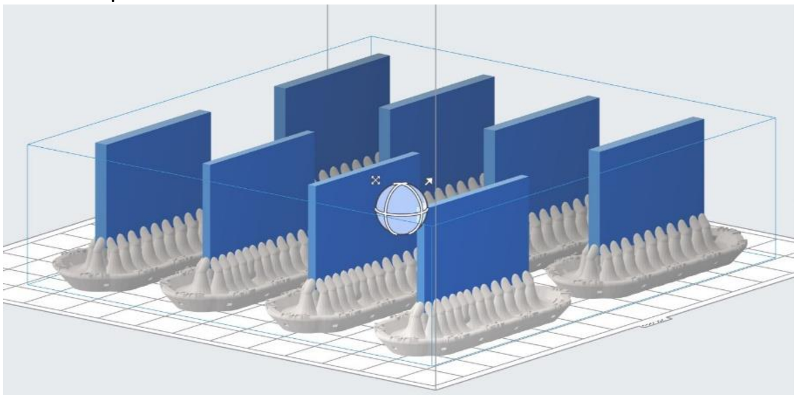
Date: 21-5-2019

Printing settings:

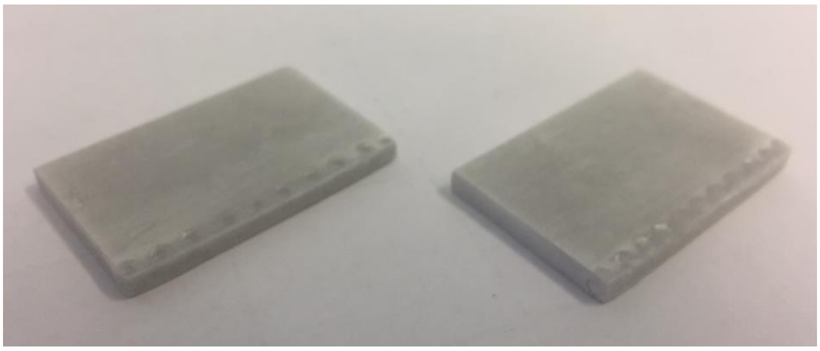
Support density	1,00
Support touch point size	2,00 mm
Printed in an angle	No, horizontally
Ceramic Z-scale factor	1,12

Duration: ~ 4,5 hours

Test sample:



Results:



Both samples printed successfully. No flaws or deformations are visible.

Alcohol procedure

Both samples were left in the alcohol basin for certain amounts of time. Sample 6 was left in the basin for 24 hours and sample 7 for 48 hours. Sample 7 was put in the basin first and sample 6 24 hours later so they could be removed from the basin at the same time and be fired afterwards when still wet.

Firing

Purpose:
The purpose of this test is to understand the impact of firing a wet sample on the material characteristics. The liquid inside the samples can have an influence on the vitrification process and

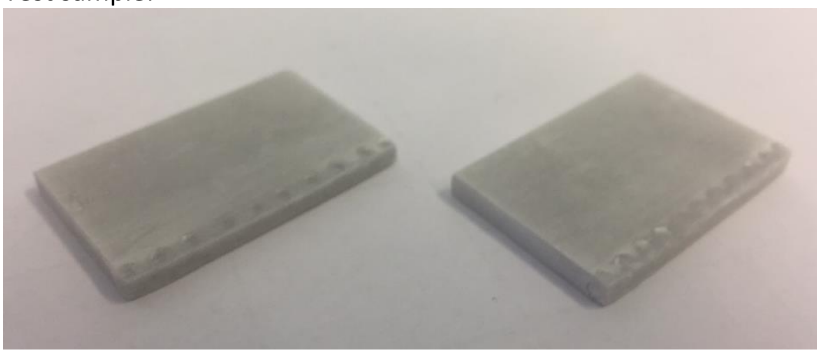
make the samples more porous. So, it will be researched if this is actually the case and what the samples would look like. The samples are fired together with IV-2.2, V-1 and VI. A burnout hold time of 8 hours is used because samples IV-2.2 have a thickness of 4 mm. These samples and samples V-1 and VI are all thinner so this burnout hold time will work fine for these samples as well.

Date: 23-5-2019

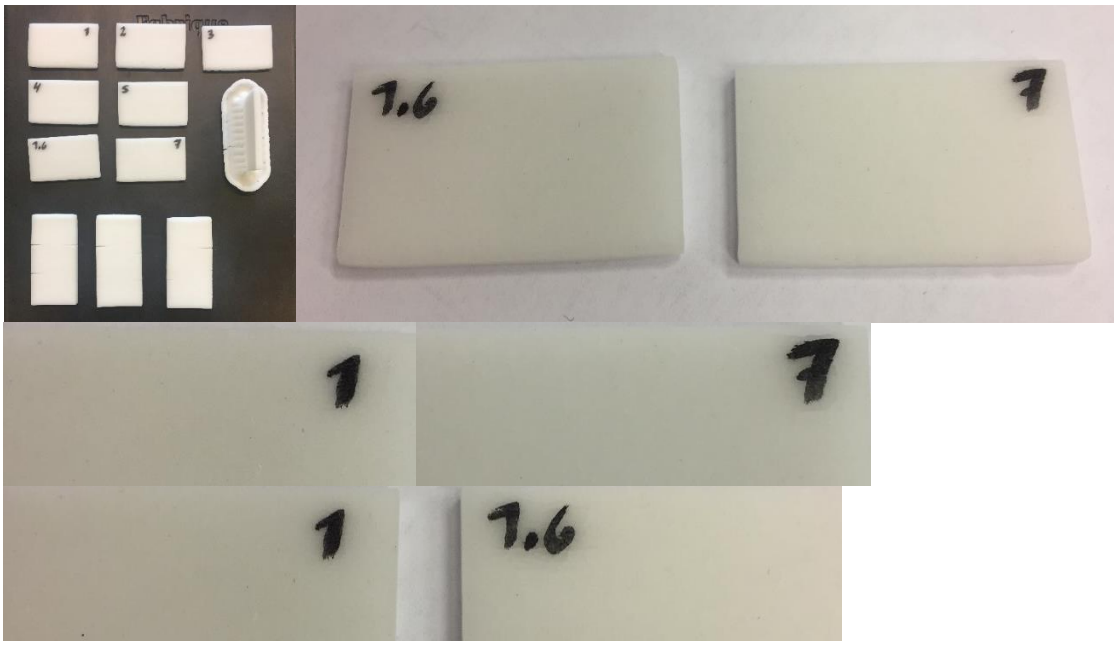
Firing schedule

Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	8	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**35,5**	

Test sample:



Results:



There is a clear difference between samples which are fired dry or wet. Samples 6 and 7 are more porous and have clear surface textures. They have small cracks on the surface. There is not a big difference between samples 6 and 7. Both samples have a porous surface texture.

So, firing samples when still wet will make the surface texture more porous.

V-3 Altering the kiln settings

Printing

Purpose:

The purpose of this test is to see the influence, of altering the sintering temperature, on the material characteristics. 6 samples will be printed. 3 samples with a thickness of 2.5 mm and 3 with a thickness of 2 mm. One sample with a thickness of 2.5 mm and one of 2 mm will be fired together to see the influence of the changed firing schedule on samples with different wall thicknesses.

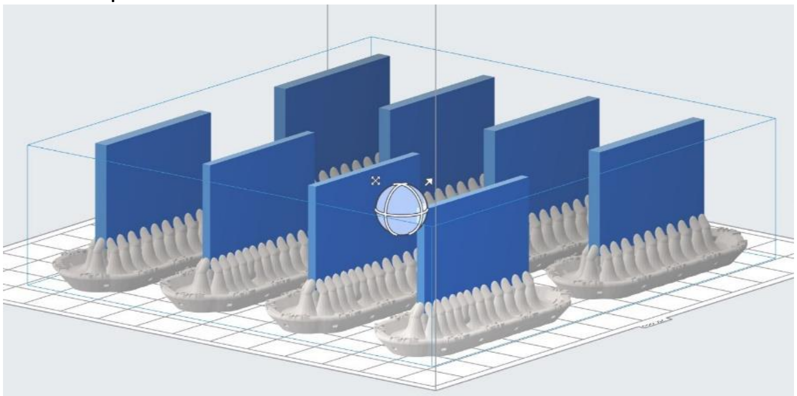
Date: 21-5-2019

Printing settings:

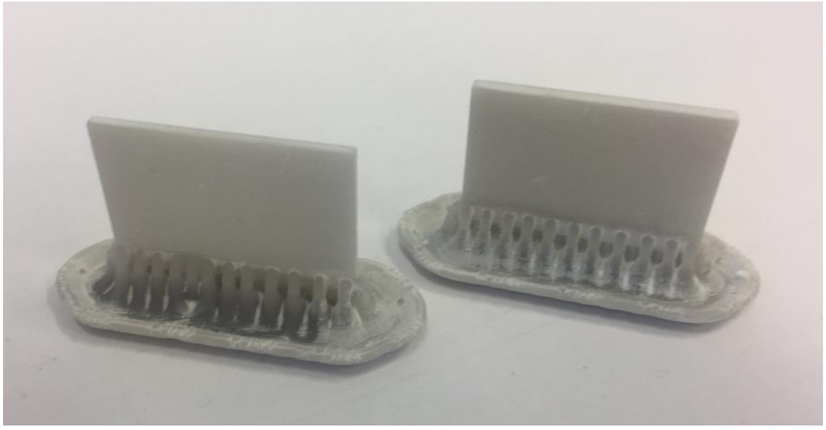
Support density	1,00
Support touch point size	2,00 mm
Printed in an angle	No, horizontally
Ceramic Z-scale factor	1,12

Duration: ~ 4,5 hours

Test sample:



Results:



All samples printed successfully without any flaws or deformations.

Firing 1250 °C

Purpose:

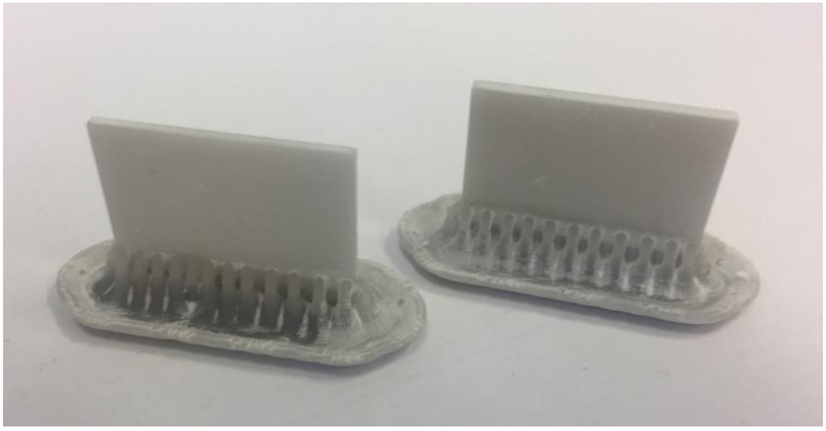
The first sample pair is going to be fired with a lower sintering temperature than normal. Normally the samples will be fired with a temperature of 1271 °C to create a vitrified non porous part. When lowering the temperature the material will probably not get vitrified completely influencing the material characteristics. So, the purpose of this test is to find out how the sintering temperature influences the material characteristics. Specifically how a lower sintering temperature influences the material characteristics.

Date: 27-5-2019

Firing schedule

Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	7	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1250	180	5,3	Ramp 2
1250 - 1250	0	0,08	Sintering hold
1250 - 900	350	1	Cool down
900 - 0	60	15	
Total		**34,4**	

Test sample:



Results:

The samples look more porous compared to a sample which is sintered at a temperature of 1271 °C. So, firing a sample using a sintering temperature of 1250 °C will create a more porous and visually and tactually rough sample.

Firing 1271 °C hold time of 10 min

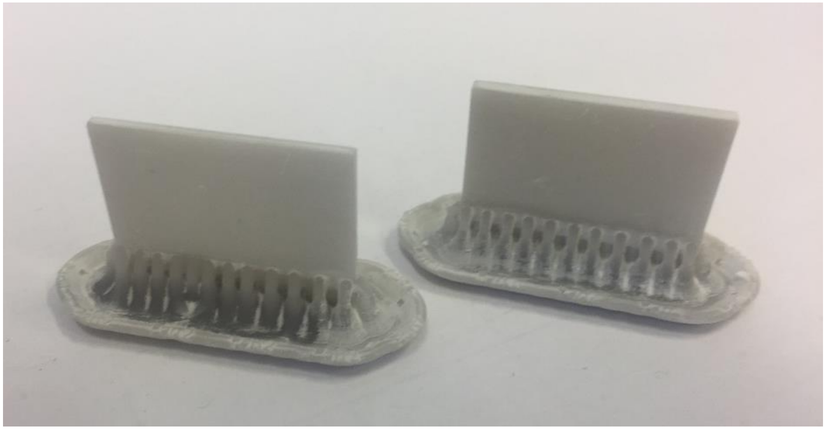
Purpose:
The second sample pair is going to be fired with the same sintering temperature as normal but with a longer sintering hold time. Normally the samples will be fired with a temperature of 1271 °C and a sintering hold time of 5 minutes to create a vitrified non porous part. When increasing the sintering hold time the material will probably get more vitrified influencing the material characteristics. So, the purpose of this test is to find out how the sintering hold time influences the material characteristics. Specifically how a longer sintering hold time influences the material characteristics.

Date: 27-5-2019

Firing schedule

Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	7	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,16	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**34,6**	

Test sample:



Results:
Unfortunately the kiln broke before this test could be executed. So, it is not clear how the sintering hold time influences the material characteristics.

Firing 1300 °C

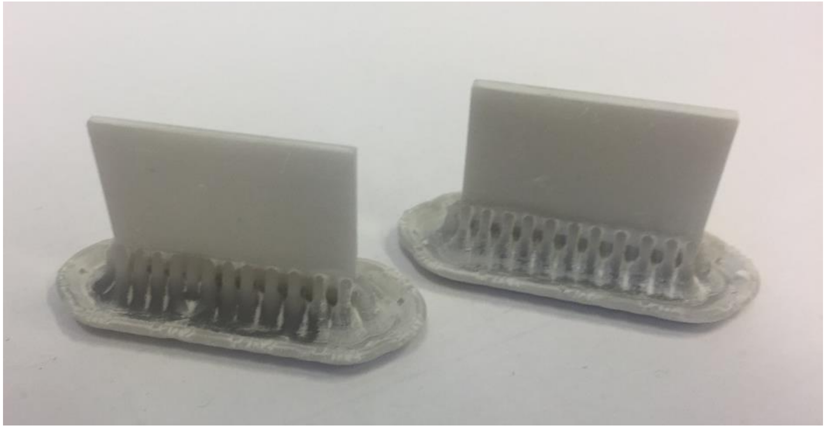
Purpose:
The third sample pair is going to be fired with a higher sintering temperature than normal. Normally the samples will be fired with a temperature of 1271 °C to create a vitrified non porous part. When increasing the temperature the material will probably get vitrified more influencing the material characteristics. So, the purpose of this test is to find out how the sintering temperature influences the material characteristics. Specifically how a higher sintering temperature influences the material characteristics.

Date: 27-5-2019

Firing schedule

Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	7	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1300	180	5,6	Ramp 2
1300 - 1300	0	0,08	Sintering hold
1300 - 900	400	1	Cool down
900 - 0	60	15	
Total		**34,6**	

Test sample:



Results:
Unfortunately the kiln broke before this test could be executed. So, it is not clear how the higher sintering temperature influences the material characteristics.

V-4 Smooth surface of samples after firing

V-4.1 Trial 1

Purpose:
Samples have a smooth side when removing them from the build plate. This smooth side is created because it is in contact with the metal build plate when printing. This support material with a smooth surface will be fired together with III-2 and III-3. It will be fired to see if the smooth surface will remain smooth or at least smoother compared to the other faces or if it will become the same roughness as the other faces. This sample is also thinner compared to the sagging samples (III-2) to the kiln setting will again be fine.

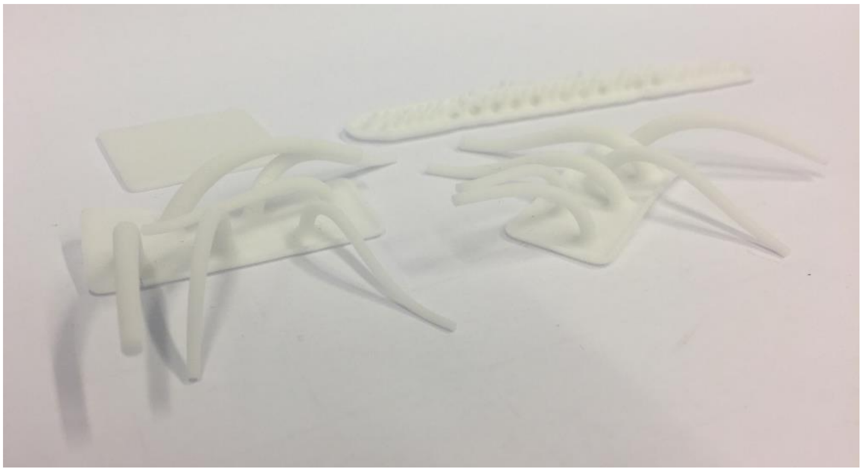
Date: 16-5-2019

Firing schedule

Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	8	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**35,5**	

Test samples:


Results:



The previously smooth surface is not smooth anymore after firing. It does look more vitrified so not as porous as the other surfaces but it still feels rough and unpleasant. So, this will not be a solutions for making the tactile experience of the material more pleasant.

V-4.2 Trial 2

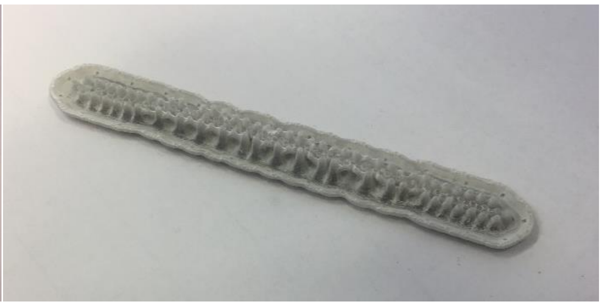
Purpose:
The purpose of this test is to fired two more support parts to be sure that the smooth surface disappears when fired. Test V-4.1 tested this already but it is always good to test multiple samples to be sure. For this test a small and a large support sample get fired. They are fired together with samples which have a wall thickness thicker than 3 mm (IV-1.2) so the burnout hold time will be set to 8 hours.

Date: 20-5-2019

Firing schedule

Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	8	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**35,5**	

Test sample:



Results:

The smooth surfaces of the support parts became rough after firing as was the case for the sample of test V-4.1. So, smooth surfaces created before firing will not remain smooth after firing. So, when wanting to make the surface texture smooth it should be done another way. Most likely after firing.

VI What happens when firing part on support

Printing

Purpose:
The purpose of this test was to see if a sample can be fired on the support. A 2.5 mm sample will be printed and the support will be left on the sample after cleaning.

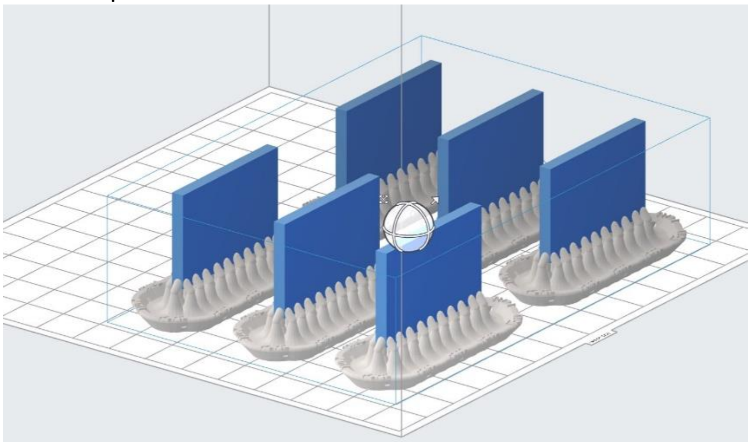
Date: 20-5-2019

Printing settings:

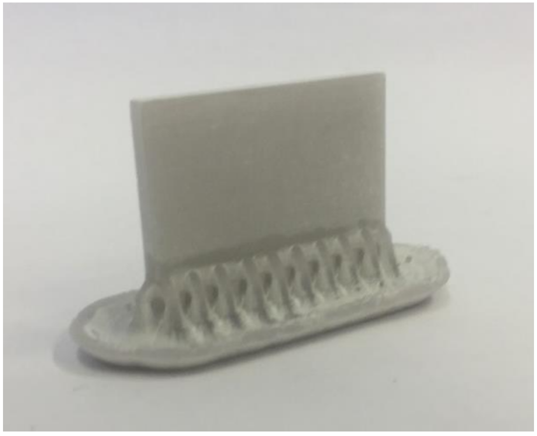
Support density	1,00
Support touch point size	2,00 mm
Printed in an angle	No, horizontally
Ceramic Z-scale factor	1,12

Duration: ~ 4 hours

Test sample:



Results:



The sample printed successfully without any flaws or deformations.

Firing

Purpose:
The sample was fired together with IV-2.2, V-1 and V-2. The IV-2.2 samples need a burnout hold time of 8 hours since they are 4 mm thick. The support sample from this test is thinner so a burnout hold time of 8 hours will work fine for this sample as well. Understanding about shape limitations is

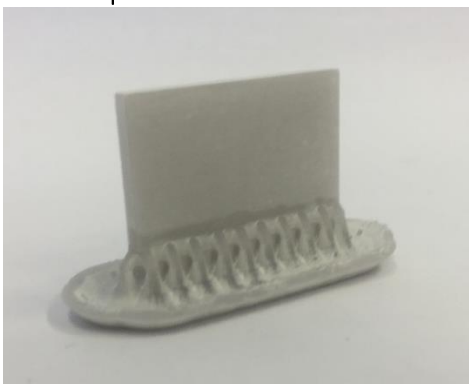
created when the sample can be fired on the support without cracking or releasing from the support. If it is possible other shapes with wire like structures could be fired without complications as well.

Date: 23-5-2019

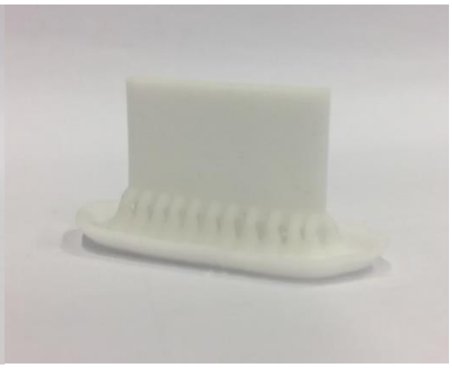
Firing schedule

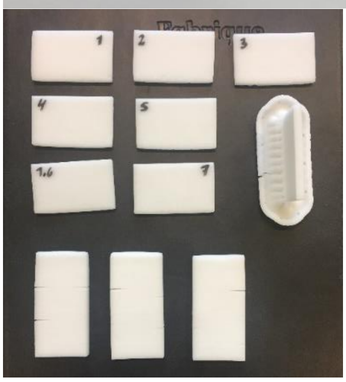
Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	8	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**35,5**	

Test sample:



Results:





Firing a sample on the support is possible. Only slight warping occurs. It is actually the same principle as firing a pot and a lid together. Both parts will have the same shrinkage and deformation when fired together making sure that the parts will fit together.

VII Hidden chambers incorporated in a cup

Printing

Purpose:

The purpose of this test is to understand if it is possible to print walls with internal chambers and structures. The material has high translucency and if it is possible to print walls with internal chambers and structures these can be hidden until the translucency is emphasized. Creating a nice hidden feature. A cup with internal chambers will be printed. The chambers have tiny holes which allow for the resin to drip out of the sample.

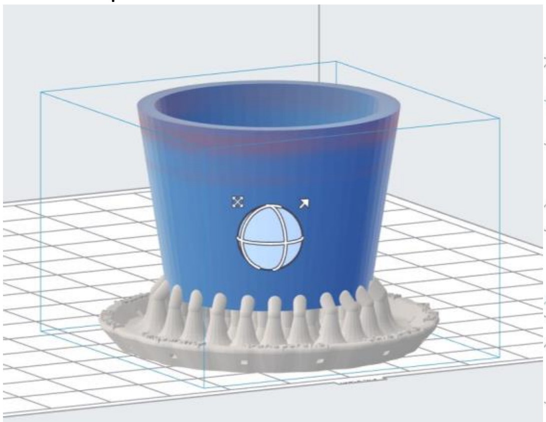
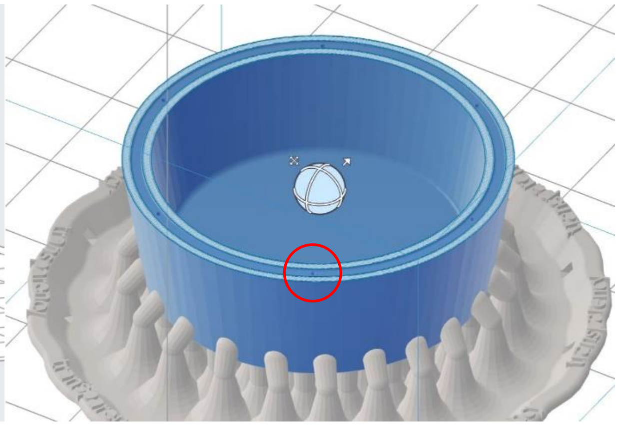
Date: 3-6-2019

Printing settings:

Support density	1,00
Support touch point size	2,00 mm
Printed in an angle	No, vertically
Ceramic Z-scale factor	1,12

Duration: ~ 3,5 hours

Test sample:

Results:


The part was printed successfully. However, it looks like one of the chambers inside the cup walls contains resin. Especially on one side of the cup which also has some small holes. The chambers are visible when holding the sample in the light but also when it is not in the light. So, it is possible to print parts which have walls with internal chambers and structures.

Firing

Purpose:
The purpose of this test is to understand if it is possible to fire samples which have walls with internal chambers or structures (sandwich structures). It can be that these internal structures will create deformations or cracks so firing this cup with internal chambers will show what happens to it when firing. It is also nice to know if these internal structures actually are hidden when the samples are not held in the light or if they are visible apart from the environment. This sample will be fired together with II-4 and VII-2.1. The samples will be fired with a burnout hold of 8 hours because the samples from test VII-2.1 have thicker walls than 3 mm.

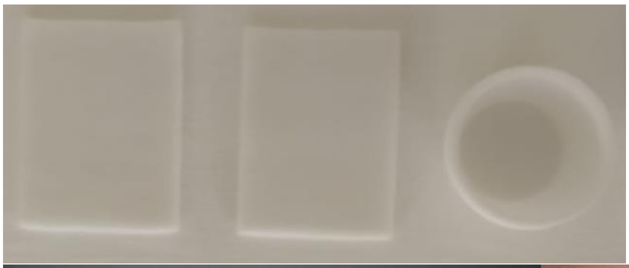
Date: 14-6-2019

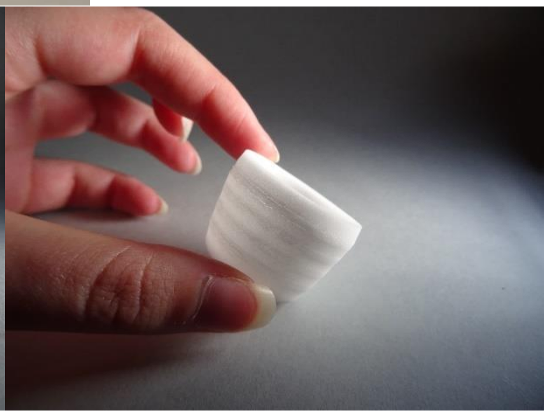
Firing schedule

Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	8	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**35,5**	

Test sample:

Results:





The cup is deformed after firing. This is because of uneven shrinkage. The chambers shrunk less than the parts without internal chambers. Because of this the cup became more rounded. The sandwich structure cracked during firing. This could be because it has very thin walls or because of possible resin inside the chambers. It can also be because or the air inside the chambers. The part of the cup which had small holes changed into a big hole after firing because of the cracking. Lastly the chambers are actually visible even when not held in the light because of the uneven shrinkage and the cracks.

VIII Focussed tinkering

VIII-1 Controlled cracking 3D

Printing

Purpose:
The previous controlled cracking tests have been executed used flat samples. Controlled cracking has not yet been tested with a 3D shapes which has continues surfaces. So, during this test controlled cracking on a shape with continues surfaces is tested. 2 cups are printed. The printing process will be paused 3 times. Every pause will be the same length now that it is known which pausing time is optimal for creating controlled cracks (IV-2.2). So, the printing process will be paused 3 times each with a duration of 5 minutes. The pauses should create prominent lines created by resin settling as was the case for the flat samples.

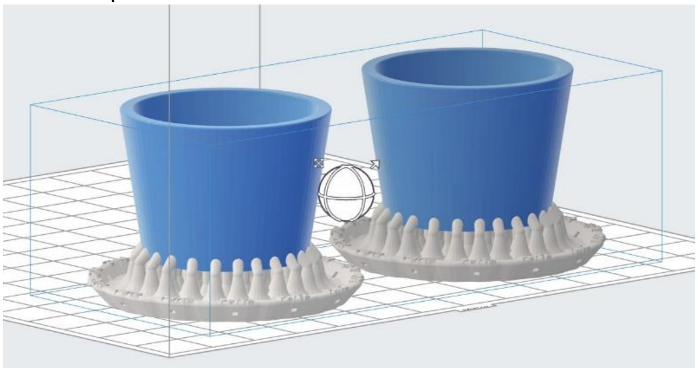
Date: 28-5-2019

Printing settings:

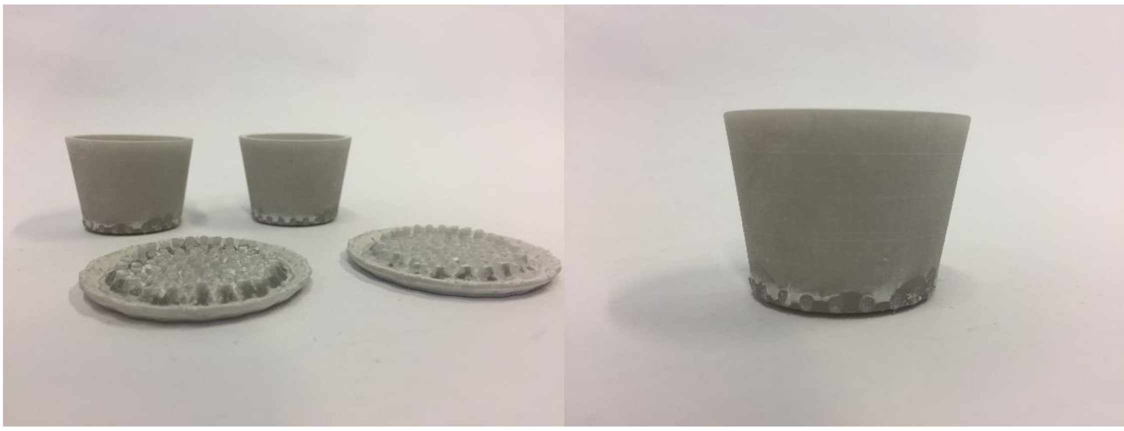
Support density	1,00
Support touch point size	2,00 mm
Printed in an angle	No, vertically
Ceramic Z-scale factor	1,12

Duration: ~ 4 hours

Test sample:



Results:



Print was a success. The prominent lines created by pausing are visible and samples don't have any other flaws or deformations.

Firing

Purpose:

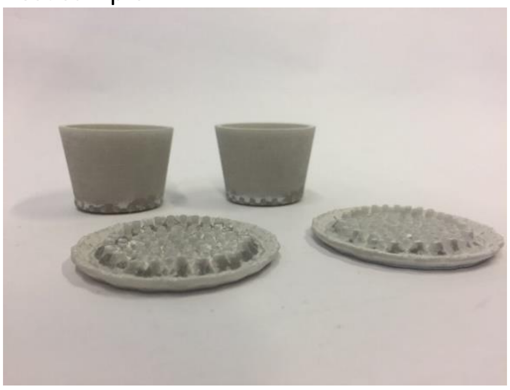
The printed samples with prominent lines, created by pausing the printing process, will be fired. For flat samples without continues surfaces these prominent lines would create cracks when fired. During this test it will be researched if these prominent lines also create cracks on continues surfaces. The samples will be fired together with focus group samples. The samples will be fired with a burnout hold of 8 hours because the focus group samples have parts which have thicker walls than 3 mm.

Date: 30-5-2019

Firing schedule

Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	8	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**35,5**	

Test sample:



Results:

The prominent lines are visible when holding the cups in the light but no clear cracks can be seen. This means that controlled cracking is possible for non-continuous surfaces like walls but not on continuous surfaces like cups.

VIII-2 Translucency

VIII-2.1 Sandwich structure incorporated in a wall

Printing

Purpose:
The purpose of this test is to understand if it is possible to print walls with internal chambers and structures. The material has high translucency and if it is possible to print walls with internal chambers and structures these can be hidden until the translucency is emphasized. Creating a nice hidden feature. During the previous test a cup with continuous surfaces was printed and this sample had some flaws when coming out of the printer. During this test two flat samples will be printed to see if these can be printed without flaws. The internal structures have tiny holes which allow for the resin to drip out of the sample.

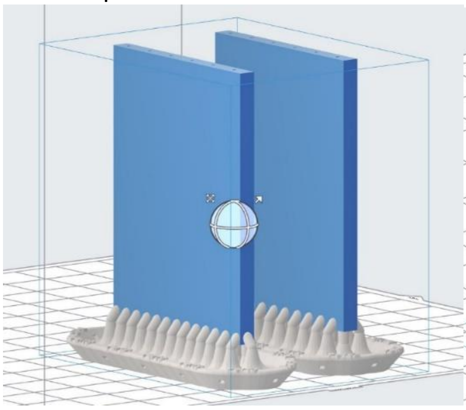
Date: 4-6-2019

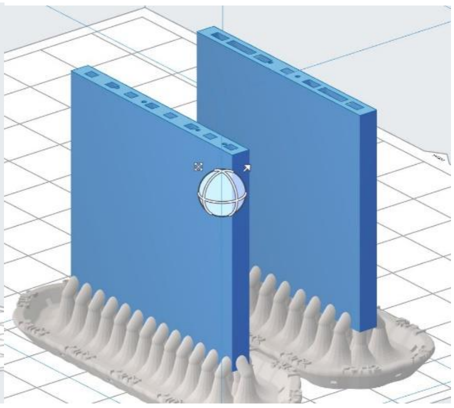
Printing settings:

Support density	1,00
Support touch point size	2,00 mm
Printed in an angle	No, vertically
Ceramic Z-scale factor	1,12

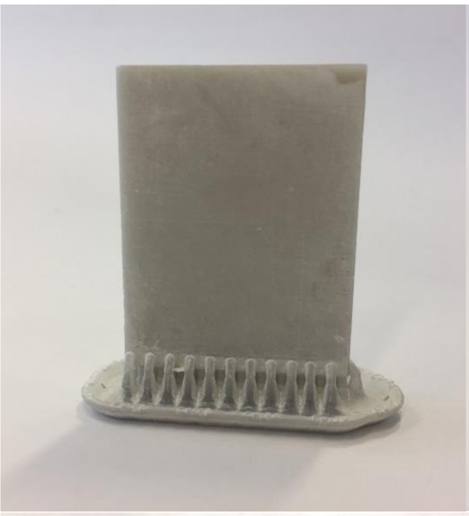
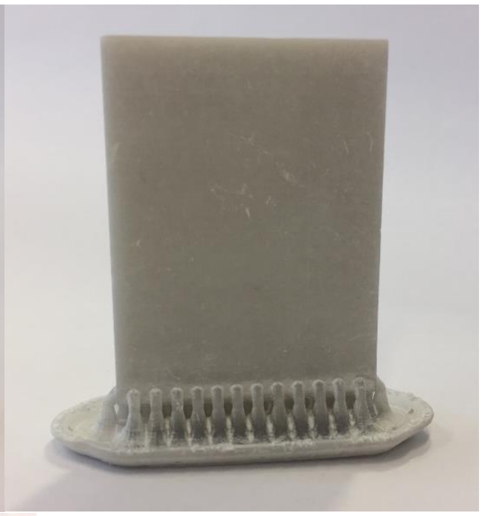
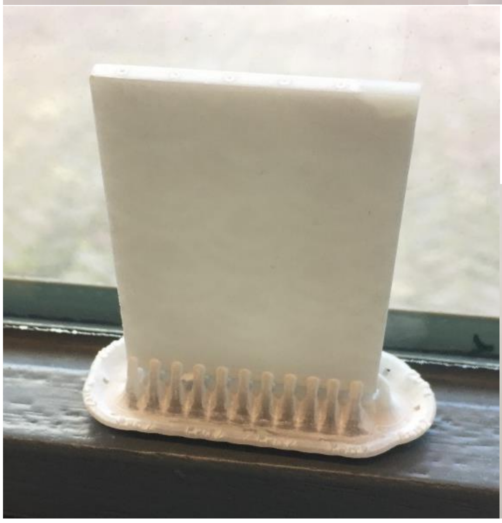
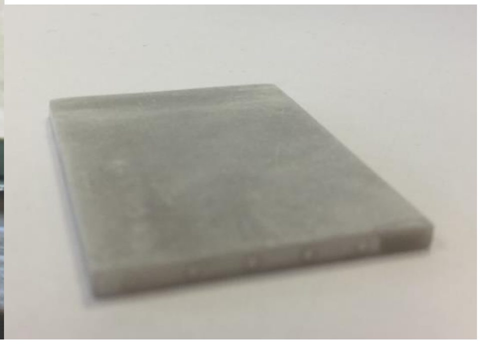
Duration: ~ 5 hours

Test sample:





Results:

The parts were printed successfully without flaws and holes. However, for one sample it looks like a part of the internal structure contains resin. The internal structures are only visible when holding the samples in the light. So, it is possible to print parts which have walls with internal chambers and structures.

Firing

Purpose:

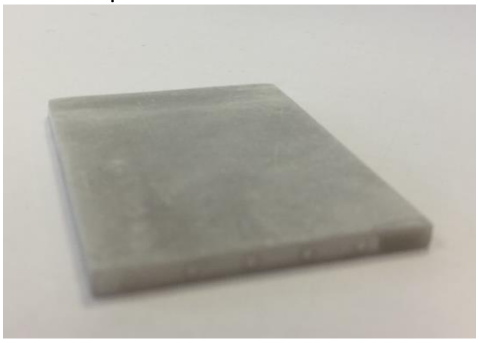
The purpose of this test is to understand if it is possible to fire samples which have walls with internal chambers or structures (sandwich structures). A cup with internal chambers has been fired during test VII-2.1 and this sample cracked and deformed during the firing process. During this test a flat sample will be fired to see if this will also crack and deform when fired. It is also nice to know if these internal structures actually are hidden when the samples are not held in the light or if they are visible apart from the environment. This sample will be fired together with II-4 and VII. The samples will be fired with a burnout hold of 8 hours because the walls are thicker than 3 mm.

Date: 14-6-2019

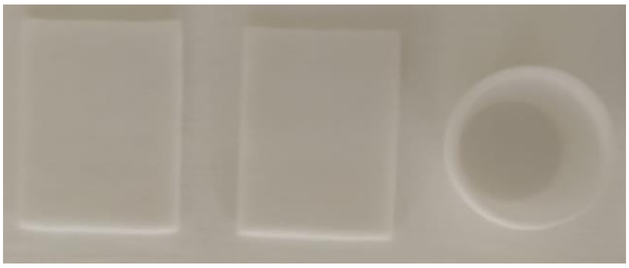
Firing schedule

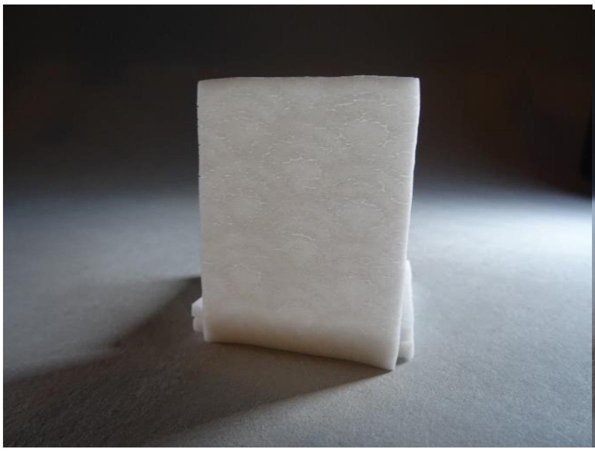
Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	8	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**35,5**	

Test sample:



Results:





The samples were slightly warped after firing but not as deformed as the cup from test VII. The sandwich structures did however crack during firing. This could be because it has very thin walls or because of possible resin inside the chambers. It can also be because of the air inside the structure. The internal structures also became more apparent after firing making them visible even when not held in the light. Since the samples shrunk the structures became rather small and not as clear as they were before so the structures should be made a bit bigger to make them more clear.

VIII-2.2 Sandwich structure incorporated in a wall & hollow sphere with texture on inside

Printing

Purpose:
The purpose of this test is to print sandwich structures which are a bit bigger than the samples from test VII-2.2 to see if they will still crack or deform when firing. Furthermore, a hollow sphere with an internal texture is printed. These samples are printed to test how these type of shapes will interact with light. The material has high translucency and these shapes and walls with internal chambers and structures can be hidden until the translucency is emphasized. Creating a nice hidden feature.

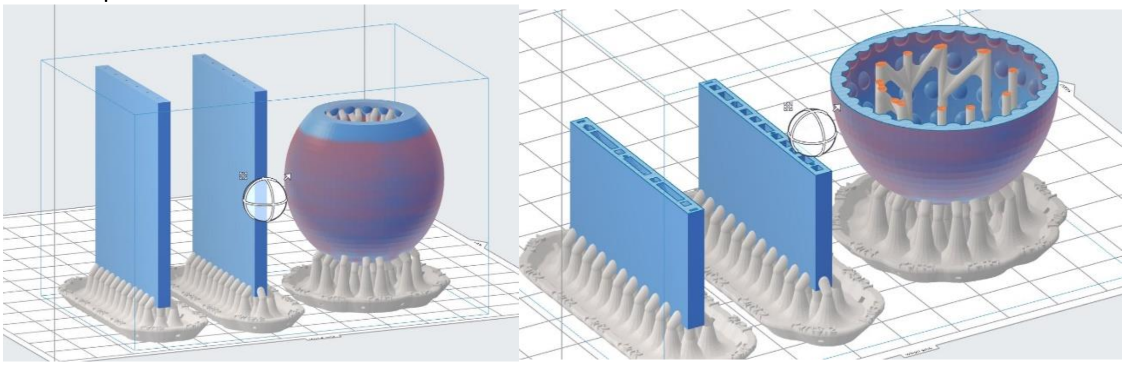
Date: 4-6-2019

Printing settings:

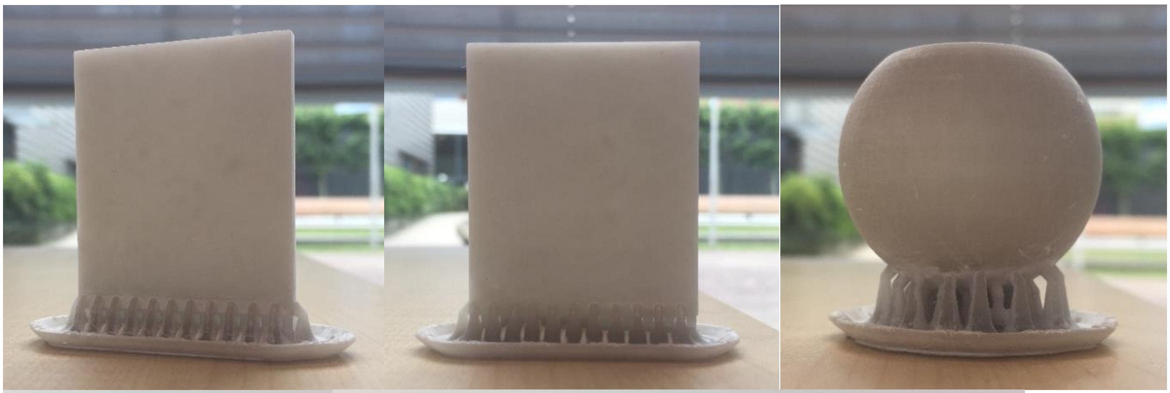
Support density	1,00
Support touch point size	2,00 mm
Printed in an angle	No, vertically
Ceramic Z-scale factor	1,12

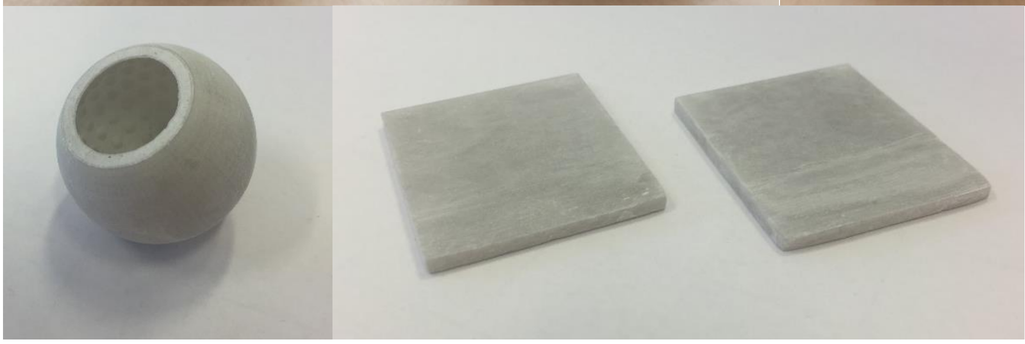
Duration: ~ 5,5 hours

Test sample:



Results:





The parts were printed successfully without flaws and holes. However, for two samples it looks like parts of the internal structures contain resin. The internal structures are only visible when holding the samples in the light. So, it is possible to print parts which have walls with internal chambers and structures.

Firing

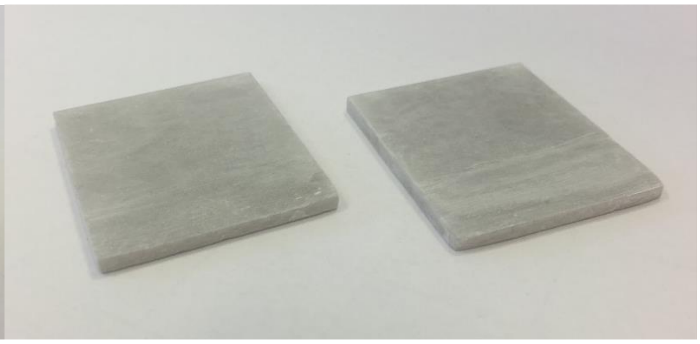
Purpose:
The purpose of this test is to see how a hollow sphere will fire. If it will collapse, deform or crack or if it will only shrink. Furthermore, slightly bigger walls than the walls from test VII-2.1 are fired to see if they will still warp and crack or if they will fire without any problems. The internal structures of these walls are also a bit bigger so hopefully they will not shrink to much and stay visible and clear after firing. lastly it is also nice to know if these internal structures actually are hidden when the samples are not held in the light or if they are visible apart from the environment. The samples will be fired with a burnout hold of 8 hours because the walls are thicker than 3 mm.

Date: 3-7-2019

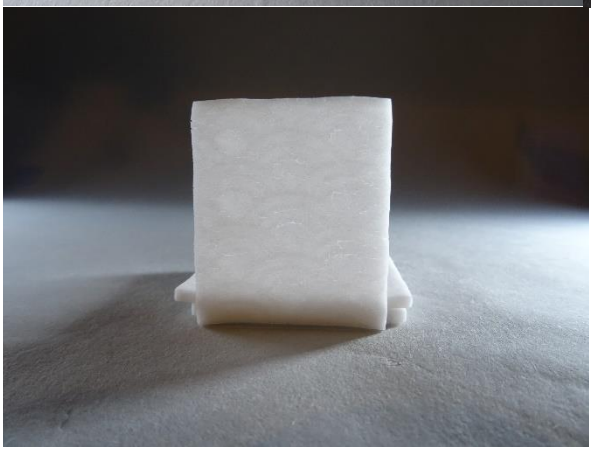
Firing schedule

Temperature [C]	Temperature/hour [C/h]	Hours [h]	
0 - 240	60	4	Ramp 1
240 - 240	0	8	Burnout hold
240 - 300	60	1	
300 - 300	0	1	
300 - 1271	180	5,4	Ramp 2
1271 - 1271	0	0,08	Sintering hold
1271 - 900	371	1	Cool down
900 - 0	60	15	
Total		**35,5**	

Test sample:

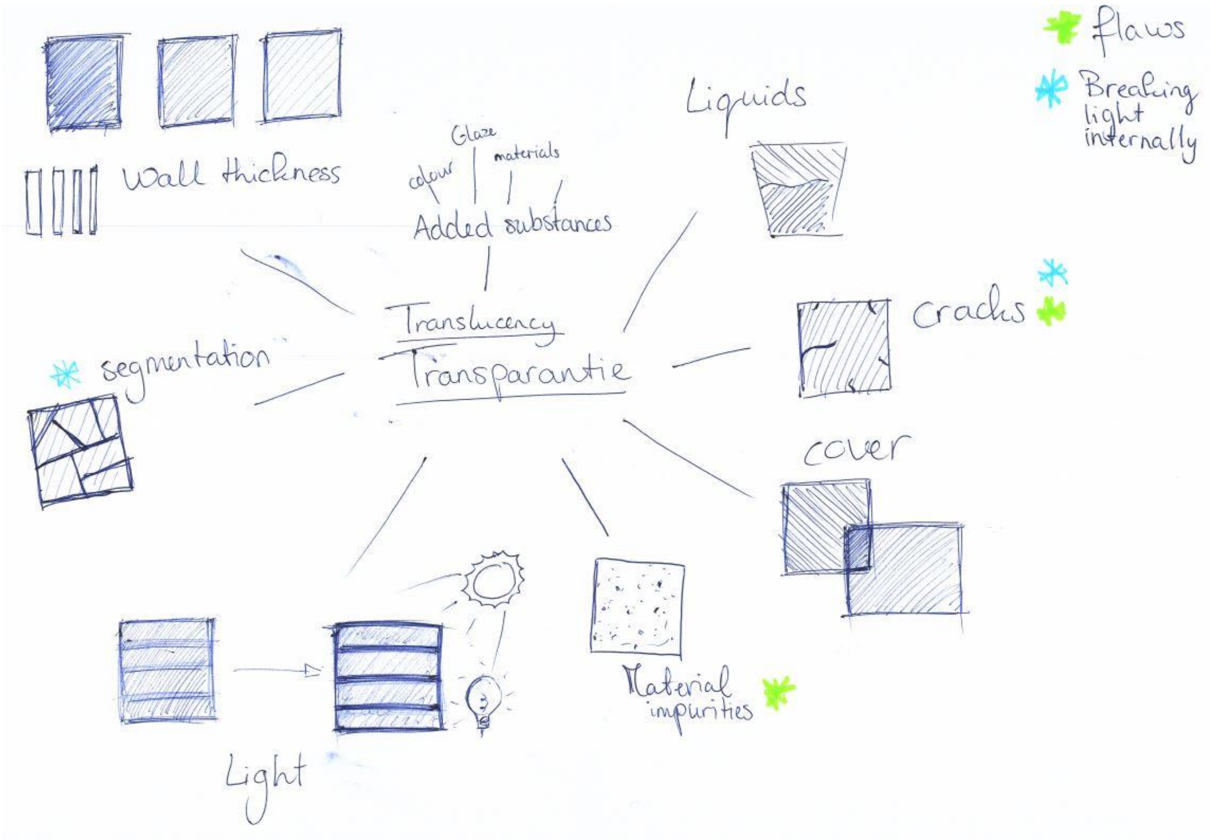


Results:



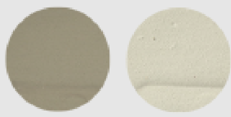
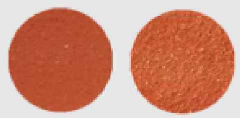
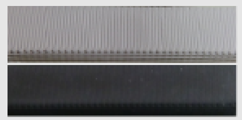
The samples were slightly warped after firing but not as deformed as the cup from test VII-2.1. The sandwich structures did however crack during firing. This could be because it has very thin walls or because of possible resin inside the chambers. It can also be because of the air inside the structure. The internal structures also became more apparent after firing making them visible even when not held in the light. Since the samples shrunk the structures became rather small and not as clear as they were before so the structures should be made a bit bigger to make them more clear.

Appendix J: Emphasizing translucency



Appendix K: Material benchmarking

Material benchmark table

Material					
Application picture / sample					
Name	TOU-LIGHT	Seams	Textured porcelain bottles	Functional 3D printed ceramics	Bioceramic medical implants
Manufacturer	Hikaru Yajima	Benjamin Hubert	Leah Kaplan	Olivier van Herpt	Amedica Corporation
Composition	Shigaraki Toto ceramics (high fire)	White body slip (Low fire)	Porcelain (high fire)	High fire stoneware clay (different colours)	Medical grade silicon nitride (Si_3N_4)
Ram state picture / sample					
Technical properties	Transmits light 3 times better than transparent porcelain Still transparent when walls have a thickness of 7-8 mm Has a warm creamy white colour Smooth texture and no impurities Can be mixed/kneaded with an opaque china clay since properties are close Good formability since it can be turned, formed by hand and casted	Ratio of 50:50 ball clay and talc Fluid so it can be casted Fast casting rate Strong greenware Smooth texture when in green state and slightly rougher texture when fired Lower strength compared to stoneware and porcelain clay Challenge to find a proper glaze fit for this material. Only low fire glaze can be used	High translucency Has a creamy white colour Smooth glassy (non porous) texture and no impurities Good formability since it can be turned, formed by hand and casted High strength and hardness High resistance to chemical attack and thermal shock	High fire hard stoneware clay does not slump during the printing process unlike commonly used wet clay. Strong greenware High strength after firing Rougher texture due to impurities inside the clay body. Wide range of colours which can be mixed to create marble and gradient effects.	Mechanical strength Resistance to thermal shock High temperature stability Hardness, Wear resistance Smooth texture, no impurities Has a combination of flexural strength and fracture toughness that are among the highest measured values for ceramic materials Biocompatible Visible on radiographic imaging
Experiential properties	The swaying flames of Senko Hanabi sparklers are mimicked by playing with wall thickness during the turning process Transparency	Highlight and play with the inevitable seams created by the slip casting production process. The seams are kept in the original condition before and after firing. Introducing decorative elements to a design, without having to carry out multiple processes.	Experiment with textures and different hand building techniques. This is possible since porcelain originaly is creamy white has a smooth texture and no impurities so, it is like a blank canvas. Furthermore its plasticity gives a lot of form freedom.	Using high fire stoneware clay gives the designer more freedom because the poor strength of the wet clay is no limitation anymore. This allows Olivier to print human scale products with high levels of detail. He is now able to play with textures, surfaces, shapes and sizes.	Since Si_3N_4 is a nonoxide ceramic it offers opportunities for altering its surface characteristics compared to other materials that are used in orthopedic or dental applications When fabricated with a microrough surface type it has shown enhanced resistance to bacterial attachment, an increase in cell growth and higher bone to implant contact when compared to other commonly used biomaterials.
Applications	Lamps Ceramic washbowls Tableware	Decorative items Tableware	Lamps Tableware, Decorative items Bathroom fittings, Tiles	Large objects Table ware Art pieces	High-end bearings, medical implants High-speed cutting tools Rocket nozzles and thrusters
Activities	Consumer product Lamp for restaurants / common area	Consumer products	Consumer products	Art pieces Collaboration with brand COS Exhibitions in EU, USA, BR, SG, UAE	Advanced, technical and medical products
Ultimate purpose	Creates a space of peace and quiet by mimicking the flames of nature and produces peace of mind Illuminate a room	Create centerpieces with one-off details while made through a mass production process. Decorate the room	Experiment with porcelain and create objects which are inspired by and even mimick basketry, paper, fabrics and other age-old materials. Decorate the room	Being able to create human scale functional FDM 3D printed ceramic objects. Optimizing the FDM 3D printing process.	Creating durable and wear proof implants which will decrease the likelihood of bacterial infections

Appendix L: Touch

In this chapter the internal and external variables, which allow for different tactile experiences, are elaborated on. Internal variables being the properties of the skin and the body and the external variables being the differences in interaction.

The skin

Touch is first of all possible due to receptors located in the skin. The skin is the largest organ of the human body. An adult has a skin surface of 1.5 to 2 m^2, is 0.5 to 4mm thick, depending on the body part, and equals to about 15% of the total body weight (Saladin, 2001). There are two types of skin that cover the body. The glabrous (hairless) skin and the hairy skin. The Glabrous skin covers the palms of the hands and the soles of the feet and the hairy skin covers the rest of the body (MacKenzie and Iberall, 1994).

The two types of skin consist of the same three layers, the epidermis, the dermis and the hypodermis. Together the layers contain a variety of receptors. Mechanoreceptors, which are sensitive to mechanical transformations of the skin. Thermoreceptors, which detect cooling or warming of the skin. Nociceptors, which partially create the sensation of pain when the skin is damaged. When the receptors get stimulated, neural fibres conduct this information to the central nervous system (Sonneveld & Schifferstein, 2008). The receptors can be divided into two categories depending on the adaption speed. There are slowly adapting and rapidly adapting receptors. The slowly adapting receptors only detect constant stimuli and the rapidly adapting receptors only detect short pulses (Rantala, n.d.).

Even though the two types of skin are made out of the same layers they do have differences. The differences between the two skin types are (MacKenzie and Iberall, 1994):

- The thickness of the skin. The epidermis of the glabrous skin is thicker, tougher and more resistant to pressure.
- Amount of grip. The epidermis of the glabrous skin contains fat pads on the fingers and bulges on the palms of the hands. These fat pads allow the skin to follow the shape and indents of the object, creating a stable grip.
- The accuracy of touch. The glabrous skin has a papillary structure. Meaning the ridges in the epidermal layer that form the palm and fingerprints. The structure has a sensory function. It allows the sensors to register lateral pressure. Contributing to the accuracy of the tactual sense. Furthermore, the ridges will offer more grip when holding and using an object.
- The distribution of the sweat glands. The sweat glands are denser distributed in the glabrous skin than in the hairy skin. Furthermore the glands also respond differently to stimuli. The glands in the glabrous skin respond to force, improving grip, and the glands in the hairy skin respond to temperature, regulating body temperature.
- Presence of the rapidly adapting Meissner's corpuscles. These corpuscles make it possible for a human to sense light touch and vibrations. The hairy skin lacks them, making it impossible to sense subtle tactual details, like texture differences, on body parts covert in hairy skin.

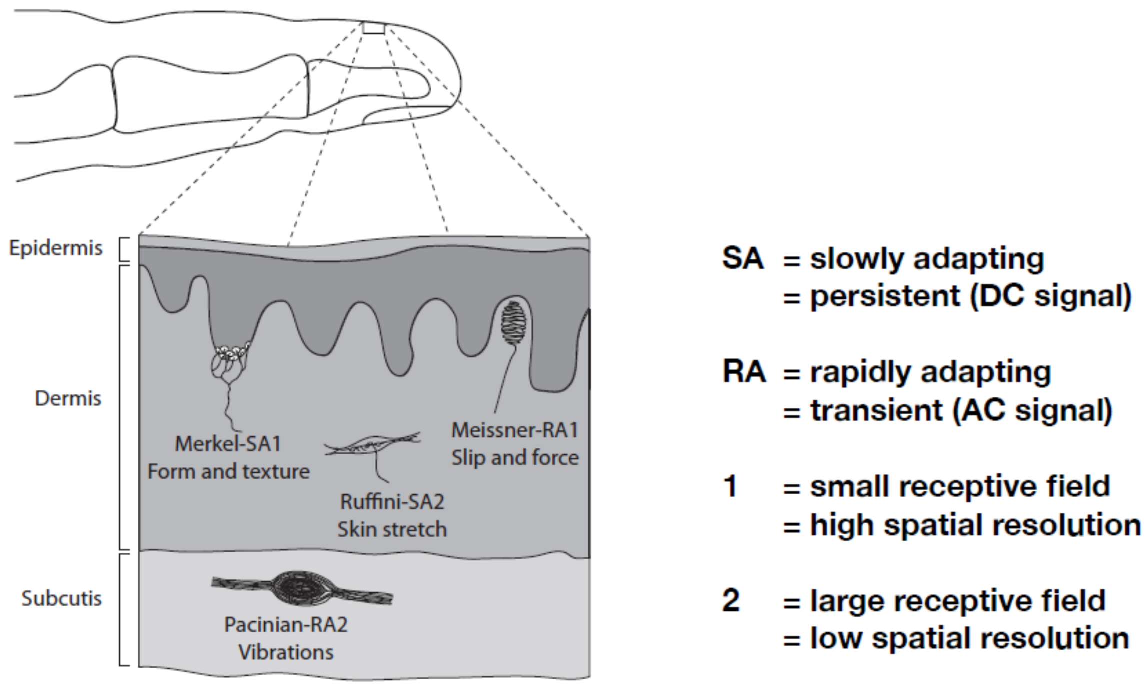
Because of these differences the two skin types fulfil different needs.

Tactual sensitivity

The amount of receptors in the skin is not equally distributed throughout the body, so the location of the stimulation has a lot of effect on the tactual experience. In the human body the fingertips and the lips contain the most receptors per mm^2 (Stevens, 1990).

Furthermore, sensitivity depends on the size of the receptive fields and distance between them. The receptive fields of the receptors in the upper skin layer are relatively small, being between 2-4mm. These fields also overlap creating a sensitive whole which is able to accurately communicate how many touch points are stimulating the skin and where the skin is stimulated exactly. The receptors situated in the deeper skin layers have larger receptive fields, making them less accurate. Giving the

tactual sensation of an inaccurate location and incorrect amount of touch points stimulating the skin (Sekuler and Blake, 1994).
Lastly the size of the receptive area in the somatosensory cortex has effect on the tactual sensitivity. The Homunculus by Penfield visualises the human body based on the size of the receptive areas in the brain. As can be seen the lips and hands cover the largest area in the cortex, while the calves and the back cover small areas.
The distribution of the receptors and the spatial characteristics or the receptor fields cannot be altered but the size of the receptive area in the brain can be altered. This can be done by training and experience and it the reason why blind people can better recognize objects and patterns (Berla and Butterfield, 1977; Craig, 1988).
Tactual sensitivity is not static and changes over time. It can decrease due to aging (Stevens and Choo, 1996), diseases (Pratorius, Kimmeskamp and Milani, 2003) and damages to the central nervous system (Franzen and Lindblom, 1976)



Skin sensations

As said, the skin contains three types of receptors and each receptor creates a different skin sensation (Saladin, 2001). The three sensation types are:

- Direct touch sensation and sensations resulting from touch.
- Warm and cold sensations
- Pain sensations

The intensity, quality, duration and location of the stimulation also influences the sensation (Gibson, 1963). So, the three sensation types mentioned above can be sub-categorised. These sub-categories are:

- Light touch. This is a level of touch which does not deform the skin. It is detected by rapidly adapting mechanoreceptors and, for example, allows people to forget about the clothes they are wearing (Saladin, 2001).
- Pressure. Pressure is a level of touch which does deform the skin. It is a lasting touch which is detected by slowly adapting mechanoreceptors. Because of this pressure sensations on the skin are difficult to ignore (Sonneveld & Schifferstein, 2008).

- Vibration. Vibration is a level of touch which does not deform the skin. It is experienced when the rapidly adapting mechanoreceptors are stimulated rhythmically. High frequency vibrations will stimulate the lower layer Pacinian corpuscles and the low frequency vibrations will stimulate the upper layer Meissner's corpuscles (Rantala, n.d.).
- Cold and warmth. These sensations are experienced through stimulation of two different thermoreceptors. The cold and warm receptors. The thermoreceptors are rapidly adapting when subject to temperatures between 20°C and 40°C, resulting in a thermally neutral sensation. When the thermoreceptors are subject to temperatures below 20°C or above 40°C, they become slowly adapting, resulting in a constant sensation of cold or warmth (Sonneveld & Schifferstein, 2008). Above 45°C, the tissue starts to be damaged. This is detected by slowly adapting nociceptors and the sensation becomes one of pain (Ganong, 2001).
- Pain. There are two types of pain. Pain induced by stimulation of the skin, called superficial pain, and muscle, bone and joint pain, called deep pain. Superficial pain is sensed because of the stimulation of the slow adapting nociceptors. There are several types of nociceptors, mechanical, thermal and chemical (Sonneveld & Schifferstein, 2008).
- Itch and tickle. These sensations are experienced by mild stimulation of receptors comparable to nociceptors. By, for example, moving something across the skin (Saladin, 2001). Besides stimulating the mechanical nociceptors, itch and tickle can be experienced by mild stimulation of chemical nociceptors.
- Physical pleasure. This sensation is experienced when someone is being mildly touched. Lightly stimulating the slowly adapting mechanical nociceptors in the hairy skin (Olausson et al., 2002).

Body sensations

A human also has muscle and joint receptors besides skin receptors. These sense the body posture and body movements which are involved in and necessary for active touch (Saladin, 2001).

Active and passive touch

There are also external variables which create different tactile experiences, besides the internal variables mentioned in the previous chapters.
The first external variable is the type of touch. There are two types of touch. Touching an object, called active touch, and being touched by an object, called passive touch (Gibson, 1962). When actively touching an object one is exploring the object's properties. When passively touching the object one experiences sensations in the body and what is being done to the body (Gibson, 1962). However, when being touched by an object one can still be aware of object properties. So touching and being touched can occur at the same time during a physical interaction. It mainly depends on where someone's attention is directed to. Towards the object, towards personal sensations caused by the object or towards both (Sonneveld & Schifferstein, 2008).
The location of the active or passive touch has effect on the sensation. Since, some body parts are more suitable for touching and some more for being touched. As said before, the hairy skin does not contain Meissner's corpuscles, making it unfit for feeling light touch and vibrations. So, the hairy skin is better fit to communicate the location of a tactile stimulation. Whereas, the glabrous skin on the hands and the soles of the feet is better fit for active touch (Bolanowski, 2004).
Besides directly touching or being directly touched by an object or person people can also touch the environment and its objects through other objects (Burton, 1993). These objects can either be extensions of the body like nails, teeth and hair, referred to as accessory organs (Saladin, 2001). Or man-made object's like hammers, knifes and rackets.

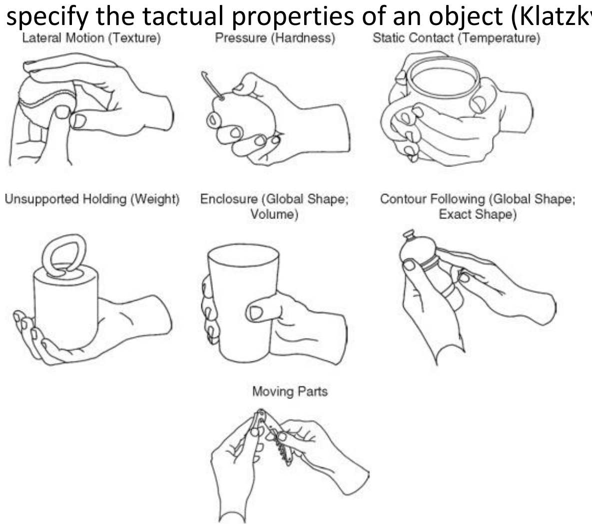
Motivation for interaction

Another external variable is the motivation for interaction. There are several reasons why people interact with products. These reasons are (Sonneveld & Schifferstein, 2008):

- Interaction for practical, functional use. When the motivation for use is purely functional the object is often used as a tool. It creates a human-world interaction through the functional object. These functional objects are tools like scissors, knifes and camera's. Objects are mostly used for their intended functionality. However, they are sometimes used for unintended purposes like opening a jar with scissors.
- Interaction to play. Objects can also be used for non-functional reasons. One of these non-functional reasons is playing. Someone can play with objects which are developed with the intension of playing. Like yo-yo's and hockey sticks. But many people play with objects which don't have a playing functionality. They will physically interact with the object because it creates pleasant sensations.
- Interaction to take care for and be taken care of. Objects are often made and used for care taking. There are different types of care taking. The first type is when an object is used by people for personal care and support. Examples of objects used for this type of interaction are hair brushes, tooth brushes, chairs and beds. The second type of care taking is when people are taking care of an object. How people take care of objects is by, for example, washing, repairing and storing it. Objects used for personal care and support have care taking as their main functionality but the interaction of taking care can also be with an object which has another main functionality. Like warming oneself with a warm coffee mug.
- Interaction to explore. Regardless of the function, one can touch an object with the intention of exploring the tactual properties. This can be the exploration of an unknown object with the purpose of discovering how it feels. But it is also common for people to explore known objects with the purpose of just being in contact with them.
- Interaction to carry. This is an interaction which is functionality based. When objects are movable or portable one will carry them. Carrying can be done in, for example, someone's hands, in a pocket and on someone's back.
- Interaction by accident, by coincidence. The last interaction motivation is based on coincidence. Not all interactions are intentional. They can happen by accident like sitting on something unexpected or bumping into something.

Movement

The last external variable is the difference in exploratory movements. One of the interaction motivations was to explore. When actively exploring, people use specific movements to be able to specify the tactual properties of an object (Klatzky et al., 1985).



The tactual properties of an object can be divided into four categories (Sonneveld & Schifferstein, 2008):

- The substance. The hardness, stiffness, elasticity, temperature and weight of the object's material.
- The surface. The texture and the patterns of the object.
- The structure. The global shape, the exact shape, the volume and the weight distribution of the object.
- Moving parts. How the parts move in relation to each other.

These categories can be sub-categorised and each specific property with corresponding exploratory movement is described below.

- Hardness, stiffness and elasticity. These properties are explored by movements which try to transform the object. Hardness and softness are explored by applying pressure (Klatzky, Lederman and Reed, 1987) and stiffness and flexibility are explored by bending and twisting (Ashby and Johnson, 2002). Elasticity and plasticity are explored by applying pressure or tension and observing what happens when the tension or pressure is released. The material has high elasticity when the object returns to its initial shape and high plasticity when it remains transformed (Sonneveld & Schifferstein, 2008).
- Temperature. Extremely high or low temperatures are explored differently than temperatures close to the body temperature. Extremely high or low temperatures are felt instantaneously and create a strong reaction of withdrawal. Unthreatening temperatures need more time to be perceived. So, these temperatures are explored by keeping one's hands on one spot for a certain amount of time. This makes it possible to perceive the difference between body temperature and temperature of the object.
  Materials which extract warmth from the skin at a fast rate are perceived as cold. When a material does not extract warmth at all or at a slow rate it is perceived as warm (Sonneveld & Schifferstein, 2008). The temperature perception becomes more accurate as the difference between object temperature and skin temperature increases (Tritsch, 1988).
- Texture and patterns. Textures and patterns are explored by stroking the surface of the object. Stroking is necessary for the detection of fine surface textures (Hollins and Risner, 2000). However, coarser surface textures may already be explored through static touch (Lederman, 1981). Textures can also be explored by holding the object. This allows the assessment of the grip, so the amount of friction.
  The perception of roughness is dependent on the location. The lips and fingers are most sensitive to roughness while the back and the thighs are least sensitive (Stevens, 1990). The perception of roughness is also dependent on the intensity of the movement. A texture will be perceived as rougher when the applied finger force is increased (Lederman, 1974). The conditions of the skin also influence the perception of grip and roughness. Slightly wet hands will create a greater friction force so more grip and very wet hands will cause slipping so les grip.
- Shape and size of the object. Shape and size are explored by grasping, holding, manipulating and following the contours of an object. Besides this, the size and shape of larger objects can be explored through dynamic touch. Meaning by, for example, swinging them.
  The perceived shape and size of an object can be influenced by what has been explored beforehand. For example, after one has been exploring concave surfaces for an extended amount of time, flat surfaces are perceived as convex and vice versa (Vogels, Kappers and Koenderink, 2001).
- Weight and balance. The weight of an object is explored by holding and by moving it up and down. Weight distribution is explored through dynamic touch. By swinging the object or trying to hold it in a specific position (Turvey, 1996). Weight is expressed as heavy or light and weight distribution as balanced or unbalanced.
  The weight perception can be influenced by the size of an object. A subject holding two objects, different in size but equal in weight, perceives the larger object as lighter (Murray et

al., 1999). Weight perception is also influenced by what has been explored beforehand as is the case for shape and size.

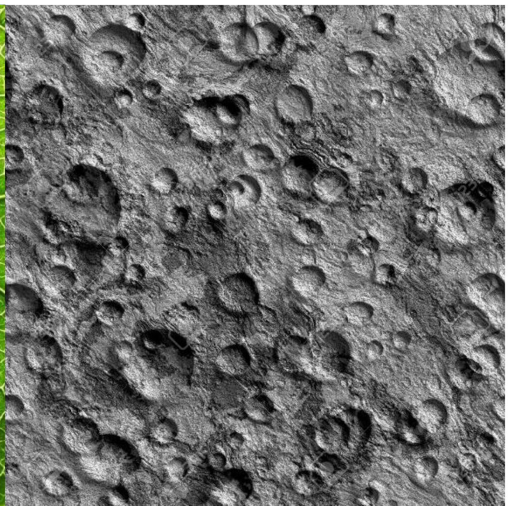
With the newly required knowledge about touch and the different types of interaction a tactility research can be set up. The test set up and results are described in the next chapter.

Appendix M: Pleasant tactility

The characteristics of the original material are (focus group):
Hard
Rough
Cold
Matte
Not reflective
Not elastic
Translucent
Touch
Weak
A bit heavy

It was found in multiple papers (Roberta, Spence and Gallace, 2014; Klöcker et al., 2012; Klöcker et al., 2013; Etzi and Gallace, 2016) that smooth surfaces are linked to pleasantness and rough surfaces are linked to unpleasantness. This was confirmed during the small test executed during this research (appendix N).
Furthermore, a result from the focus group was that incongruence between visual input and tactile input creates unpleasantness.
Pleasant textures found in literature are soft, fibered materials, like velvet and terry cloth or smooth materials like paper and silk.
The material cannot be made soft or fibered. So, the focus should be on pleasant materials which are hard and not soft and fibered.

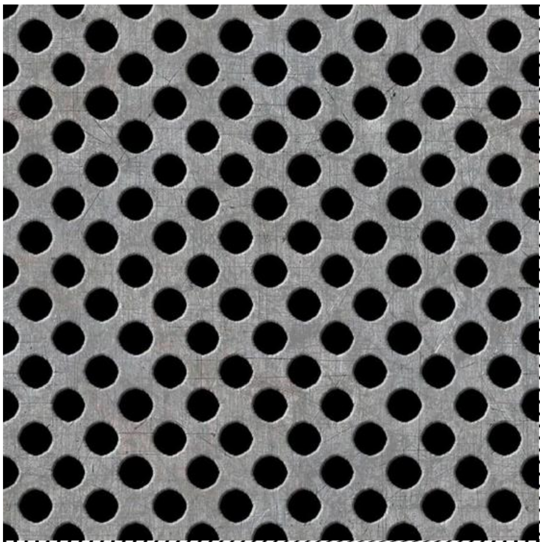
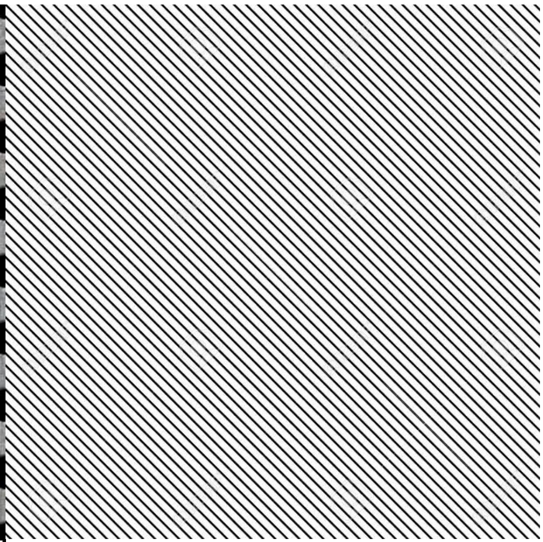
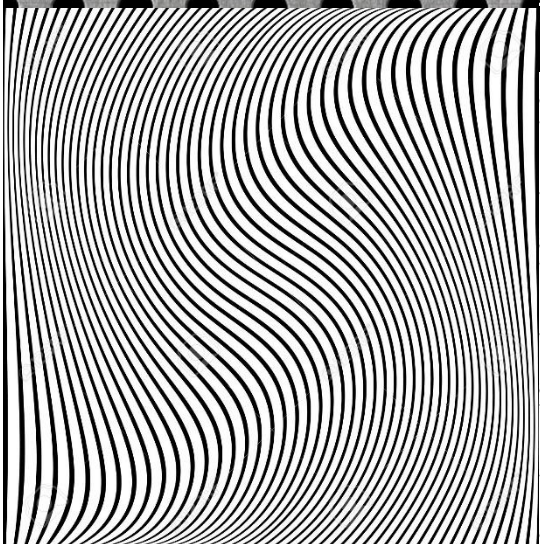
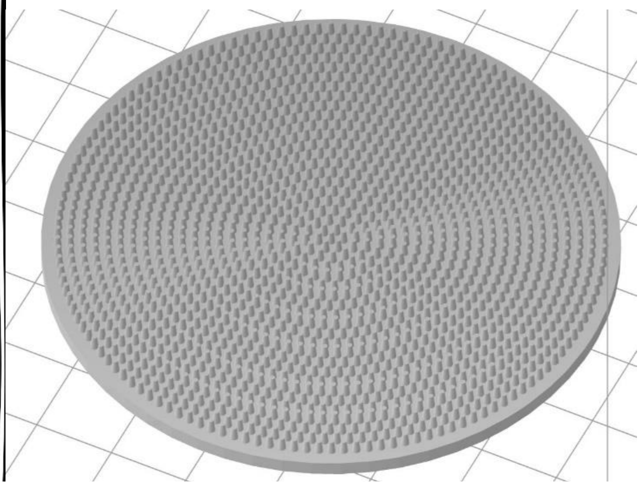
It was found that wood and rough leather were found pleasant. This inspired to search textures in nature. Four textures inspired by nature were chosen shown below.

Two of the textures are actually hard (wood and moon surface) and two are actually flexible. It was still expected that even though they are soft they could create a positive tactile experience.

The last 4 textures were chosen based on information gathered through an interview with Jess O'Brien and literature research. Jess O'Brien explained that stick and slip actually influence the perceived roughness of a material. Meaning, a material which has a structured displacement, like holes or spikes, will be perceived as tactually smooth because the contact area is actually smaller creating slip.

This information inspired the next four textures.

Appendix N: Pleasant & unpleasant surfaces test

Purpose

The purpose of this test was to understand what type of surface textures were found tactually pleasing and to get inspiration for the textures that were going to used in the tactility test.

Participants

The test was executed with 8 participants. All were industrial design engineering student since this target group was easily accessible.

Stimuli

The participants brought the stimuli themselves. They each brought two tactually pleasing objects and two tactually offensive objects.

Procedure

The procedure of the test was set up in four short rounds. During each round one of the 4 stimuli would be experienced and the participants were asked to explain why they found it tactually pleasing or offensive. They were also asked to interact with the objects as they would normally to observe how they actually use the objects and if the texture might be pleasant because of the type of interaction.

Results

Mostly smooth surfaces were found tactually pleasing. Surfaces like anodised aluminium and soft touch rubber coating. But also soft fabrics like, velvet, cotton and leather. Textured surface were found pleasing when grip was required.

Unpleasing surface textures were textures that create stick like rubber, fabrics with brabs and glue on lint rollers. Furthermore, surfaces which were moist like dirt were found offensive. Chalkboard type surfaces were also found offensive and lastly cheap feeling materials were found tactually offensive. Like thin shiny plastics and flimsy cardboard.

Conclusion

Smooth materials were mostly found tactually pleasing so making the Formlabs material smooth should remove the tactile offensiveness. The material itself could be made smooth by polishing or glazing but research should be done on making a surface perceived as being smooth using textures.

The Formlabs material probably creates the same effect as fabrics with barbs because of the surface roughness holding on to the skin creating stick and making the experience unpleasant.

Appendix O: Emotion sheet

D

Participant: Gender:

1	2	3	4	5	6	7	8	9
Attraction Frustration Fascination Calmness Unbelief Curiosity Confidence Outrage Comfort Doubt Boredom Excitement Pleasure Distrust Satisfaction Disapproval Surprise Trust Disgust	Attraction Frustration Fascination Calmness Unbelief Curiosity Confidence Outrage Comfort Doubt Boredom Excitement Pleasure Distrust Satisfaction Disapproval Surprise Trust Disgust	Attraction Frustration Fascination Calmness Unbelief Curiosity Confidence Outrage Comfort Doubt Boredom Excitement Pleasure Distrust Satisfaction Disapproval Surprise Trust Disgust	Attraction Frustration Fascination Calmness Unbelief Curiosity Confidence Outrage Comfort Doubt Boredom Excitement Pleasure Distrust Satisfaction Disapproval Surprise Trust Disgust	Attraction Frustration Fascination Calmness Unbelief Curiosity Confidence Outrage Comfort Doubt Boredom Excitement Pleasure Distrust Satisfaction Disapproval Surprise Trust Disgust	Attraction Frustration Fascination Calmness Unbelief Curiosity Confidence Outrage Comfort Doubt Boredom Excitement Pleasure Distrust Satisfaction Disapproval Surprise Trust Disgust	Attraction Frustration Fascination Calmness Unbelief Curiosity Confidence Outrage Comfort Doubt Boredom Excitement Pleasure Distrust Satisfaction Disapproval Surprise Trust Disgust	Attraction Frustration Fascination Calmness Unbelief Curiosity Confidence Outrage Comfort Doubt Boredom Excitement Pleasure Distrust Satisfaction Disapproval Surprise Trust Disgust	Attraction Frustration Fascination Calmness Unbelief Curiosity Confidence Outrage Comfort Doubt Boredom Excitement Pleasure Distrust Satisfaction Disapproval Surprise Trust Disgust

Appendix P: Results tactility test

Round 1: Visual exploration

Round 1: Visual	Mean	N	Std. Deviation
1.1 Sample inspired by wood	4,93	15	2,549
2.1 Sample inspired by leafs	4,20	15	2,957
3.1 Sample inspired by moon surface	5,67	15	2,664
4.1 Sample inspired by leather	4,13	15	1,995
5.1 Sample without texture	5,73	15	2,520
6.1 Sample with symmetrical lines	5,13	15	2,356
7.1 Sample with symmetrical wavy lines	3,60	15	2,261
8.1 Sample with symmetrical holes	5,73	15	3,105
9.1 Sample with symmetrical spikes	5,87	15	2,295

Temporary ranking order from most pleasant to least pleasant is:

1. Wavy lines
2. Leather
3. Leaf
4. Wood
5. Straight lines
6. Moon surface
7. Untextured
8. Holes
9. Spikes

Test Statistics[a]	
N	15
Chi-Square	11,289
df	8
Asymp. Sig.	,186

a. Friedman Test

The Friedman test does not measure a significant difference between any of the samples. Meaning that the rank order is completely coincidental. To be sure that this is the case the Wilcoxon signed rank test and the paired sample T-test were executed.

Wilcoxon signed rank test:
When taking a significance level of $p<0.05$
Wavy lines was found significantly more pleasant than:

- Moon surface ($p = 0.030$)
- Untextured ($p = 0.042$)
- Spikes ($p = 0.028$)

When taking a significance level of $p<0.10$
Wavy lines was found significantly more pleasant than holes ($p = 0.056$)
Leaf was found significantly more pleasant than moon surface ($p = 0.086$)
Leather was found significantly more pleasant than spikes ($p = 0.068$)

Paired sample T-test:
Using a significance level of $p<0.05$
The Paired samples T-test generates the same significant differences as found using the Wilcoxon signed rank test.
Wavy lines was found significantly more pleasant than:

- Moon surface ($p = 0.024$)
- Untextured ($p = 0.037$)
- Spikes ($p = 0.037$)

When using a significance level of $p<0.10$
One of the significant differences found using the Wilcoxon test is not significant anymore.
Wavy lines was found significantly more pleasant than holes ($p = 0.065$)
Leather was found significantly more pleasant than spikes ($p = 0.065$)

So, only 3 significant pairs found from the 36
1 is more pleasant than 6, 7 and 9
No significant differences between 1 – 5
No significant differences between 6 – 9

Round 2: Visual and tactual exploration

Round 2: Visual + tactual	Mean	N	Std. Deviation
1.2 Sample inspired by wood round 2	2,73	15	2,314
2.2 Sample inspired by leafs round 2	5,93	15	2,576
3.2 Sample inspired by moon surface round 2	3,87	15	2,748
4.2 Sample inspired by leather round 2	4,87	15	1,959
5.2 Sample without texture round 2	6,60	15	2,667
6.2 Sample with symmetrical lines round 2	5,27	15	2,685
7.2 Sample with symmetrical wavy lines round 2	3,93	15	2,154
8.2 Sample with symmetrical holes round 2	6,27	15	2,154
9.2 Sample with symmetrical spikes round 2	5,53	15	1,846

Temporary ranking order from most pleasant to least pleasant is:

1. Wood
2. Moon surface
3. Wavy lines
4. Leather
5. Straight lines
6. Spikes
7. Leaf
8. Holes
9. Untextured

Test Statistics[a]	
N	15
Chi-Square	25,938
df	8
Asymp. Sig.	,001

a. Friedman Test

Friedman test does measure a great significant difference between the 9 samples (p = 0.001).
The Wilcoxon signed rank test and the Paired sample T-test will clarify which sample are significantly different from one another.

Wilcoxon signed rank test:
When taking a significance level of p<0.05
Wood was found significantly more pleasant than:

- Leather (p = 0.009)
- Straight lines (p = 0.046)
- Spikes (p = 0.012)
- Leaf (p = 0.008)
- Holes (p = 0.008)
- Untextured (p = 0.015)

Moon was found significantly more pleasant than:

- Leaf (p = 0.022)
- Holes (p = 0.049)

Wavy lines was found significantly more pleasant than:

- Holes (p = 0.024)
- Untextured (p = 0.009)

Straight lines were found significantly more pleasant than untextured (p = 0.045)

When taking a significance level of p<0.10
Wood was found significantly more pleasant than wavy lines (p = 0.052)
Moon surface was found significantly more pleasant than:

- Spikes (p = 0.086)
- Untextured (p = 0.073)

Wavy lines was found significantly more pleasant than:

- Straight lines (p = 0.076)
- Spikes (p = 0.067)
- Leaf (p = 0.087)

Leather was found significantly more pleasant than holes (p = 0.064)

Paired samples T-test:
Using a significance level of p<0.05
The results of Paired samples T-test were almost corresponding with the results of the Wilcoxon signed rank test.
One of the significant differences found using the Wilcoxon test is not significant anymore.
Wood was found significantly more pleasant than:

- Leather (p = 0.003)
- Straight lines (p = 0.038)
- Spikes (p = 0.008)
- Leaf (p = 0.003)
- Holes (p = 0.002)
- Untextured (p = 0.006)

Moon was found significantly more pleasant than leaf (p = 0.017)
Wavy lines was found significantly more pleasant than:

- Holes (p = 0.025)
- Untextured (p = 0.004)

Straight lines were found significantly more pleasant than untextured (p = 0.038)

Using a significance level of p<0.10
Two of the significant differences found using the Wilcoxon test are not significant anymore.
Moon surface was found significantly more pleasant than:

- Untextured (p = 0.053)
- Spikes (p = 0.052)

- Holes (p = 0.051)

Wavy lines was found significantly more pleasant than:

- Spikes (p = 0.063)
- Leaf (p = 0.069)

Leather was found significantly more pleasant than holes (p = 0.061)

So, 11 significant pairs found from the 36
1 is more pleasant than 4 – 9
2 is more pleasant than 7 and 8
3 is more pleasant than 8 and 9
5 is more pleasant than 9
No significant differences between 1 – 3
No significant differences between 2 – 6
No significant differences between 6 – 9

Round 3: Visual and tactual exploration with light

Round 3: Visual, tactual & light	Mean	N	Std. Deviation
1.3 Sample inspired by wood round 3	2,27	15	1,280
2.3 Sample inspired by leafs round 3	3,73	15	2,463
3.3 Sample inspired by moon surface round 3	3,87	15	2,446
4.3 Sample inspired by leather round 3	4,73	15	1,944
5.3 Sample without texture round 3	6,53	15	2,615
6.3 Sample with symmetrical lines round 3	6,00	15	2,268
7.3 Sample with symmetrical wavy lines round 3	3,73	15	2,017
8.3 Sample with symmetrical holes round 3	7,27	15	1,710
9.3 Sample with symmetrical spikes round 3	6,87	15	1,457

Temporary ranking order from most pleasant to least pleasant is:

1. Wood
2. Leaf
3. Wavy lines
4. Moon surface
5. Leather
6. Straight lines
7. Untextured
8. Spikes
9. Holes

Test Statistics[a]	
N	15
Chi-Square	48,018
df	8
Asymp. Sig.	,000

a. Friedman Test

Friedman test does measure a great significant difference between the 9 samples (p = 0.000). The Wilcoxon signed rank test and the Paired sample T-test will clarify which sample are significantly different from one another.

Wilcoxon signed rank test:
When taking a significance level of p<0.05
Wood was found significantly more pleasant than:

- Wavy lines (p = 0.022)
- Moon surface (p = 0.036)
- Leather (p = 0.003)
- Straight lines (p = 0.002)
- Untextured (p = 0.002)
- Spikes (p = 0.001)
- Holes (p = 0.001)

Leaf was found significantly more pleasant than:

- Untextured (p = 0.035)
- Spikes (p = 0.004)
- Holes (p = 0.003)

Wavy lines was found significantly more pleasant than:

- Straight lines (p = 0.003)
- Untextured (p = 0.003)
- Spikes (p = 0.003)
- Holes (p = 0.001)

Moon surface was found significantly more pleasant than:

- Untextured (p = 0.043)
- Spikes (p = 0.003)
- Holes (p = 0.005)

Leather was found significantly more pleasant than:

- Spikes (p = 0.005)
- Holes (p = 0.004)

When taking a significance level of p<0.10
Wood was found significantly more pleasant than leaf (p = 0.088)
Leaf was found significantly more pleasant than:

- Leather (p = 0.091)
- Straight lines (p = 0.086)

Moon surface was found significantly more pleasant than straight lines (p = 0.073)

Paired samples T-test:
Using a significance level of p<0.05
The results of Paired samples T-test were all corresponding with the results of the Wilcoxon signed rank test.
Wood was found significantly more pleasant than:

- Wavy lines (p = 0.017)
- Moon surface (p = 0.034)
- Leather (p = 0.001)
- Straight lines (p = 0.000)
- Untextured (p = 0.000)
- Spikes (p = 0.000)
- Holes (p = 0.000)

Leaf was found significantly more pleasant than:

- Untextured (p = 0.021)
- Spikes (p = 0.001)
- Holes (p = 0.000)

Wavy lines was found significantly more pleasant than:

- Straight lines (p = 0.001)
- Untextured (p = 0.000)
- Spikes (p = 0.001)
- Holes (p = 0.000)

Moon surface was found significantly more pleasant than:

- Untextured (p = 0.033)
- Spikes (p = 0.001)
- Holes (p = 0.001)

Leather was found significantly more pleasant than:

- Spikes (p = 0.002)
- Holes (p = 0.001)

Using a significance level of p<0.10
The results of Paired samples T-test were all corresponding with the results of the Wilcoxon signed rank test.
Wood was found significantly more pleasant than leaf (p = 0.083)
Leaf was found significantly more pleasant than:

- Leather (p = 0.091)
- Straight lines (p = 0.063)

Moon surface was found significantly more pleasant than straight lines (p = 0.077)

So, 22 significant pairs found from the 36
1 is more pleasant than 3 – 9
2 is more pleasant than 6 – 9
3 is more pleasant than 6 – 9
4 is more pleasant than 6 – 9
5 is more pleasant than 8 and 9
No significant differences between 1 and 2
No significant differences between 2 – 5
No significant differences between 6 – 9

Between rounds
Wood

Report

	1.1 Sample inspired by wood	1.2 Sample inspired by wood round 2	1.3 Sample inspired by wood round 3
Mean	4,93	2,73	2,27
N	15	15	15
Std. Deviation	2,549	2,314	1,280

Temporary score from most pleasant to least pleasant is:

1. Visual, tactual and light
2. Visual and tactual
3. Visual

The Wilcoxon signed rank test and the paired sample T-test will clarify if there is a significant difference and if so which of the three rounds had significantly different scores.

Wilcoxon signed rank test:

Test Statistics[a]

	1.2 Sample inspired by wood round 2 - 1.1 Sample inspired by wood	1.3 Sample inspired by wood round 3 - 1.1 Sample inspired by wood	1.3 Sample inspired by wood round 3 - 1.2 Sample inspired by wood round 2
Z	-2,161[b]	-2,923[b]	-,962[b]
Asymp. Sig. (2-tailed)	,031	,003	,336

a. Wilcoxon Signed Ranks Test

b. Based on positive ranks.

Using a significance level of $p<0.05$
Wood had significant differences between rounds
Wood was found significantly more pleasant when experienced visually and tactually than only visual ($p = 0.031$)
Wood was found significantly more pleasant when experienced visually, tactually and in the light than only visual ($p = 0.003$)

Paired samples T-test:

Paired Samples Test

			Pair 1: 1.1 Sample inspired by wood - 1.2 Sample inspired by wood round 2	Pair 2: 1.1 Sample inspired by wood - 1.3 Sample inspired by wood round 3	Pair 3: 1.2 Sample inspired by wood round 2 - 1.3 Sample inspired by wood round 3
Paired Differences	Mean		2,200	2,667	,467
	Std. Deviation		3,448	2,498	1,552
	Std. Error Mean		,890	,645	,401
	95% Confidence Interval of the Difference	Lower	,291	1,284	-,393
		Upper	4,109	4,050	1,326
t			2,471	4,135	1,164
df			14	14	14
Sig. (2-tailed)			,027	,001	,264

The results of Paired samples T-test were corresponding with the results of the Wilcoxon signed rank test.

Leaf

Report	2.1 Sample inspired by leafs	2.2 Sample inspired by leafs round 2	2.3 Sample inspired by leafs round 3
Mean	4,20	5,93	3,73
N	15	15	15
Std. Deviation	2,957	2,576	2,463

Temporary score from most pleasant to least pleasant is:

1. Visual, tactual and light
2. Visual
3. Visual and tactual

The Wilcoxon signed rank test and the paired sample T-test will clarify if there is a significant difference and if so which of the three rounds had significantly different scores.

Wilcoxon signed rank test:

Test Statistics[a]	2.2 Sample inspired by leafs round 2 - 2.1 Sample inspired by leafs	2.3 Sample inspired by leafs round 3 - 2.1 Sample inspired by leafs	2.3 Sample inspired by leafs round 3 - 2.2 Sample inspired by leafs round 2
Z	-1,809[b]	-,634[c]	-3,078[c]
Asymp. Sig. (2-tailed)	,070	,526	,002

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.

c. Based on positive ranks.

Using a significance level of $p<0.05$

Leaf had a significant difference between rounds

Leaf was found significantly more pleasant when experienced visually, tactually and in the light than only visual and tactually ($p = 0.002$)

Paired samples T-test:

Paired Samples Test			Pair 1 2.1 Sample inspired by leafs - 2.2 Sample inspired by leafs round 2	Pair 2 2.1 Sample inspired by leafs - 2.3 Sample inspired by leafs round 3	Pair 3 2.2 Sample inspired by leafs round 2 - 2.3 Sample inspired by leafs round 3
Paired Differences	Mean		-1,733	,467	2,200
	Std. Deviation		3,634	3,204	1,971
	Std. Error Mean		,938	,827	,509
	95% Confidence Interval of the Difference	Lower	-3,746	-1,308	1,108
		Upper	,279	2,241	3,292
t			-1,847	,564	4,322
df			14	14	14
Sig. (2-tailed)			,086	,582	,001

The results of Paired samples T-test were corresponding with the results of the Wilcoxon signed rank test.

Moon surface

Report	3.1 Sample inspired by moon surface	3.2 Sample inspired by moon surface round 2	3.3 Sample inspired by moon surface round 3
Mean	5,67	3,87	3,87
N	15	15	15
Std. Deviation	2,664	2,748	2,446

Temporary score from most pleasant to least pleasant is:

1. Visual, tactual and light
2. Visual and tactual
3. Visual

The Wilcoxon signed rank test and the paired sample T-test will clarify if there is a significant difference and if so which of the three rounds had significantly different scores.

Wilcoxon signed rank test:

Test Statistics[a]	3.2 Sample inspired by moon surface round 2 - 3.1 Sample inspired by moon surface	3.3 Sample inspired by moon surface round 3 - 3.1 Sample inspired by moon surface	3.3 Sample inspired by moon surface round 3 - 3.2 Sample inspired by moon surface round 2
Z	-2,179[b]	-2,147[b]	-,214[c]
Asymp. Sig. (2-tailed)	,029	,032	,831

a. Wilcoxon Signed Ranks Test

b. Based on positive ranks.

c. Based on negative ranks.

Using a significance level of $p<0.05$

Moon surface had significant differences between rounds

Moon surface was found significantly more pleasant when experienced visually and tactually than only visual ($p = 0.029$)

Moon surface was found significantly more pleasant when experienced visually, tactually and in the light than only visual ($p = 0.032$)

Paired samples T-test:

Paired Samples Test			Pair 1: 3.1 Sample inspired by moon surface - 3.2 Sample inspired by moon surface round 2	Pair 2: 3.1 Sample inspired by moon surface - 3.3 Sample inspired by moon surface round 3	Pair 3: 3.2 Sample inspired by moon surface round 2 - 3.3 Sample inspired by moon surface round 3
Paired Differences	Mean		1,800	1,800	,000
	Std. Deviation		2,883	2,731	1,512
	Std. Error Mean		,745	,705	,390
	95% Confidence Interval of the Difference	Lower	,203	,288	-,837
		Upper	3,397	3,312	,837
t			2,418	2,553	,000
df			14	14	14
Sig. (2-tailed)			,030	,023	1,000

The results of Paired samples T-test were corresponding with the results of the Wilcoxon signed rank test.

Leather

Report	4.1 Sample inspired by leather	4.2 Sample inspired by leather round 2	4.3 Sample inspired by leather round 3
Mean	4,13	4,87	4,73
N	15	15	15
Std. Deviation	1,995	1,959	1,944

Temporary score from most pleasant to least pleasant is:

1. Visual
2. Visual, tactual and light
3. Visual and tactual

The Wilcoxon signed rank test and the paired sample T-test will clarify if there is a significant difference and if so which of the three rounds had significantly different scores.

Wilcoxon signed rank test:

Test Statistics[a]	4.2 Sample inspired by leather round 2 - 4.1 Sample inspired by leather	4.3 Sample inspired by leather round 3 - 4.1 Sample inspired by leather	4.3 Sample inspired by leather round 3 - 4.2 Sample inspired by leather round 2
Z	-1,165[b]	-,809[b]	-,489[c]
Asymp. Sig. (2-tailed)	,244	,418	,625

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.

c. Based on positive ranks.

Using a significance level of $p<0.05$

Leather had no significant differences between rounds

Paired samples T-test:

Paired Samples Test			Pair 1: 4.1 Sample inspired by leather - 4.2 Sample inspired by leather round 2	Pair 2: 4.1 Sample inspired by leather - 4.3 Sample inspired by leather round 3	Pair 3: 4.2 Sample inspired by leather round 2 - 4.3 Sample inspired by leather round 3
Paired Differences	Mean		-,733	-,600	,133
	Std. Deviation		2,576	2,501	1,302
	Std. Error Mean		,665	,646	,336
	95% Confidence Interval of the Difference	Lower	-2,160	-1,985	-,588
		Upper	,693	,785	,854
t			-1,102	-,929	,397
df			14	14	14
Sig. (2-tailed)			,289	,369	,698

The results of Paired samples T-test were corresponding with the results of the Wilcoxon signed rank test.

Untextured

Report	5.1 Sample without texture	5.2 Sample without texture round 2	5.3 Sample without texture round 3
Mean	5,73	6,60	6,53
N	15	15	15
Std. Deviation	2,520	2,667	2,615

Temporary score from most pleasant to least pleasant is:

1. Visual
2. Visual, tactual and light
3. Visual and tactual

The Wilcoxon signed rank test and the paired sample T-test will clarify if there is a significant difference and if so which of the three rounds had significantly different scores.

Wilcoxon signed rank test:

Test Statistics[a]

	5.2 Sample without texture round 2 - 5.1 Sample without texture	5.3 Sample without texture round 3 - 5.1 Sample without texture	5.3 Sample without texture round 3 - 5.2 Sample without texture round 2
Z	-1,167[b]	-,812[b]	-,367[c]
Asymp. Sig. (2-tailed)	,243	,417	,713

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.

c. Based on positive ranks.

Using a significance level of $p<0.05$

Untextured had no significant differences between rounds

Paired samples T-test:

Paired Samples Test

			Pair 1: 5.1 Sample without texture - 5.2 Sample without texture round 2	Pair 2: 5.1 Sample without texture - 5.3 Sample without texture round 3	Pair 3: 5.2 Sample without texture round 2 - 5.3 Sample without texture round 3
Paired Differences	Mean		-,867	-,800	,067
	Std. Deviation		3,441	3,121	1,280
	Std. Error Mean		,888	,806	,330
	95% Confidence Interval of the Difference	Lower	-2,772	-2,529	-,642
		Upper	1,039	,929	,775
t			-,976	-,993	,202
df			14	14	14
Sig. (2-tailed)			,346	,338	,843

The results of Paired samples T-test were corresponding with the results of the Wilcoxon signed rank test.

Straight lines

Report	6.1 Sample with symmetrical lines	6.2 Sample with symmetrical lines round 2	6.3 Sample with symmetrical lines round 3
Mean	5,13	5,27	6,00
N	15	15	15
Std. Deviation	2,356	2,685	2,268

Temporary score from most pleasant to least pleasant is:
1. Visual
2. Visual and tactual
3. Visual, tactual and light

The Wilcoxon signed rank test and the paired sample T-test will clarify if there is a significant difference and if so which of the three rounds had significantly different scores.

Wilcoxon signed rank test:

Test Statistics[a]	6.2 Sample with symmetrical lines round 2 - 6.1 Sample with symmetrical lines	6.3 Sample with symmetrical lines round 3 - 6.1 Sample with symmetrical lines	6.3 Sample with symmetrical lines round 3 - 6.2 Sample with symmetrical lines round 2
Z	-,705[b]	-1,434[b]	-1,195[b]
Asymp. Sig. (2-tailed)	,481	,152	,232

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.

Using a significance level of p<0.05

Straight lines had no significant differences between rounds

Paired samples T-test:

Paired Samples Test			Pair 1 6.1 Sample with symmetrical lines - 6.2 Sample with symmetrical lines round 2	Pair 2 6.1 Sample with symmetrical lines - 6.3 Sample with symmetrical lines round 3	Pair 3 6.2 Sample with symmetrical lines round 2 - 6.3 Sample with symmetrical lines round 3
Paired Differences	Mean		-,133	-,867	-,733
	Std. Deviation		2,924	2,475	2,282
	Std. Error Mean		,755	,639	,589
	95% Confidence Interval of the Difference	Lower	-1,753	-2,237	-1,997
		Upper	1,486	,504	,531
t			-,177	-1,356	-1,244
df			14	14	14
Sig. (2-tailed)			,862	,196	,234

The results of Paired samples T-test were corresponding with the results of the Wilcoxon signed rank test.

Wavy lines

Report	7.1 Sample with symmetrical wavy lines	7.2 Sample with symmetrical wavy lines round 2	7.3 Sample with symmetrical wavy lines round 3
Mean	3,60	3,93	3,73
N	15	15	15
Std. Deviation	2,261	2,154	2,017

Temporary score from most pleasant to least pleasant is:

1. Visual
2. Visual, tactual and light
3. Visual and tactual

The Wilcoxon signed rank test and the paired sample T-test will clarify if there is a significant difference and if so which of the three rounds had significantly different scores.

Wilcoxon signed rank test:

Test Statistics[a]	7.2 Sample with symmetrical wavy lines round 2 - 7.1 Sample with symmetrical wavy lines	7.3 Sample with symmetrical wavy lines round 3 - 7.1 Sample with symmetrical wavy lines	7.3 Sample with symmetrical wavy lines round 3 - 7.2 Sample with symmetrical wavy lines round 2
Z	-,946[b]	-,433[b]	-,060[b]
Asymp. Sig. (2-tailed)	,344	,665	,952

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.

Using a significance level of $p<0.05$

Wavy lines had no significant differences between rounds

Paired samples T-test:

Paired Samples Test			Pair 1 7.1 Sample with symmetrical wavy lines - 7.2 Sample with symmetrical wavy lines round 2	Pair 2 7.1 Sample with symmetrical wavy lines - 7.3 Sample with symmetrical wavy lines round 3	Pair 3 7.2 Sample with symmetrical wavy lines round 2 - 7.3 Sample with symmetrical wavy lines round 3
Paired Differences	Mean		-,333	-,133	,200
	Std. Deviation		3,416	3,441	2,336
	Std. Error Mean		,882	,888	,603
	95% Confidence Interval of the Difference	Lower	-2,225	-2,039	-1,094
		Upper	1,558	1,772	1,494
t			-,378	-,150	,332
df			14	14	14
Sig. (2-tailed)			,711	,883	,745

The results of Paired samples T-test were corresponding with the results of the Wilcoxon signed rank test.

Holes

Report	8.1 Sample with symmetrical holes	8.2 Sample with symmetrical holes round 2	8.3 Sample with symmetrical holes round 3
Mean	5,73	6,27	7,27
N	15	15	15
Std. Deviation	3,105	2,154	1,710

Temporary score from most pleasant to least pleasant is:

1. Visual
2. Visual and tactual
3. Visual, tactual and light

The Wilcoxon signed rank test and the paired sample T-test will clarify if there is a significant difference and if so which of the three rounds had significantly different scores.

Wilcoxon signed rank test:

Test Statistics[a]	8.2 Sample with symmetrical holes round 2 - 8.1 Sample with symmetrical holes	8.3 Sample with symmetrical holes round 3 - 8.1 Sample with symmetrical holes	8.3 Sample with symmetrical holes round 3 - 8.2 Sample with symmetrical holes round 2
Z	-,554[b]	-2,263[b]	-1,723[b]
Asymp. Sig. (2-tailed)	,580	,024	,085

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.

Using a significance level of $p<0.05$

Holes had a significant difference between rounds

Holes was found significantly more pleasant when experienced only visually than visual, tactually and in the light ($p = 0.024$)

Paired samples T-test:

Paired Samples Test			Pair 1: 8.1 Sample with symmetrical holes - 8.2 Sample with symmetrical holes round 2	Pair 2: 8.1 Sample with symmetrical holes - 8.3 Sample with symmetrical holes round 3	Pair 3: 8.2 Sample with symmetrical holes round 2 - 8.3 Sample with symmetrical holes round 3
Paired Differences	Mean		-,533	-1,533	-1,000
	Std. Deviation		2,924	2,167	2,204
	Std. Error Mean		,755	,559	,569
	95% Confidence Interval of the Difference	Lower	-2,153	-2,733	-2,220
		Upper	1,086	-,333	,220
t			-,706	-2,741	-1,757
df			14	14	14
Sig. (2-tailed)			,492	,016	,101

The results of Paired samples T-test were corresponding with the results of the Wilcoxon signed rank test.

Spikes

Report	9.1 Sample with symmetrical spikes	9.2 Sample with symmetrical spikes round 2	9.3 Sample with symmetrical spikes round 3
Mean	5,87	5,53	6,87
N	15	15	15
Std. Deviation	2,295	1,846	1,457

Temporary score from most pleasant to least pleasant is:

1. Visual and tactual
2. Visual
3. Visual, tactual and light

The Wilcoxon signed rank test and the paired sample T-test will clarify if there is a significant difference and if so which of the three rounds had significantly different scores.

Wilcoxon signed rank test:

Test Statistics[a]	9.2 Sample with symmetrical spikes round 2 - 9.1 Sample with symmetrical spikes	9.3 Sample with symmetrical spikes round 3 - 9.1 Sample with symmetrical spikes	9.3 Sample with symmetrical spikes round 3 - 9.2 Sample with symmetrical spikes round 2
Z	-,730[b]	-1,239[c]	-2,467[c]
Asymp. Sig. (2-tailed)	,466	,215	,014

a. Wilcoxon Signed Ranks Test

b. Based on positive ranks.

c. Based on negative ranks.

Using a significance level of $p<0.05$

Spikes had a significant difference between rounds

Spikes was found significantly more pleasant when experienced visually and tactually than visual, tactually and in the light ($p = 0.014$)

Paired samples T-test:

Paired Samples Test			Pair 1 9.1 Sample with symmetrical spikes - 9.2 Sample with symmetrical spikes round 2	Pair 2 9.1 Sample with symmetrical spikes - 9.3 Sample with symmetrical spikes round 3	Pair 3 9.2 Sample with symmetrical spikes round 2 - 9.3 Sample with symmetrical spikes round 3
Paired Differences	Mean		,333	-1,000	-1,333
	Std. Deviation		2,795	2,646	1,589
	Std. Error Mean		,722	,683	,410
	95% Confidence Interval of the Difference	Lower	-1,214	-2,465	-2,213
		Upper	1,881	,465	-,454
t			,462	-1,464	-3,251
df			14	14	14
Sig. (2-tailed)			,651	,165	,006

The results of Paired samples T-test were corresponding with the results of the Wilcoxon signed rank test.

Emotions

Wood	
Calmness	60%
Attraction	47%
Pleasure	40%
Comfort	40%

Leaf	
Attraction	47%
Surprise	47%
Curiosity	33%

Wavy lines	
Calmness	67%
Attraction	60%
Comfort	33%
Satisfaction	33%
Fascination	33%

Leather	
Boredom	53%
Attraction	27%
Pleasure	27%

Moon surface	
Fascination	47%
Curiosity	40%
Calmness	33%

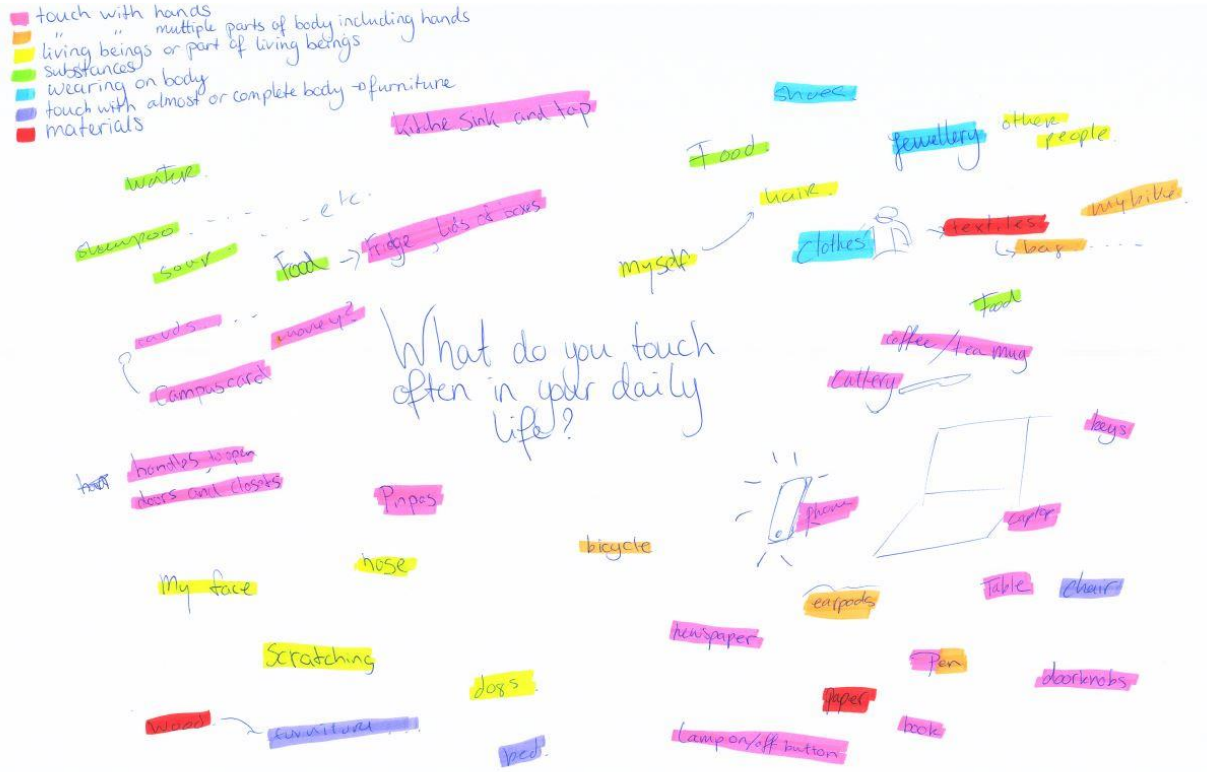
Untextured surface	
Boredom	67%
Calmness	33%
Comfort	33%
Disgust	33%

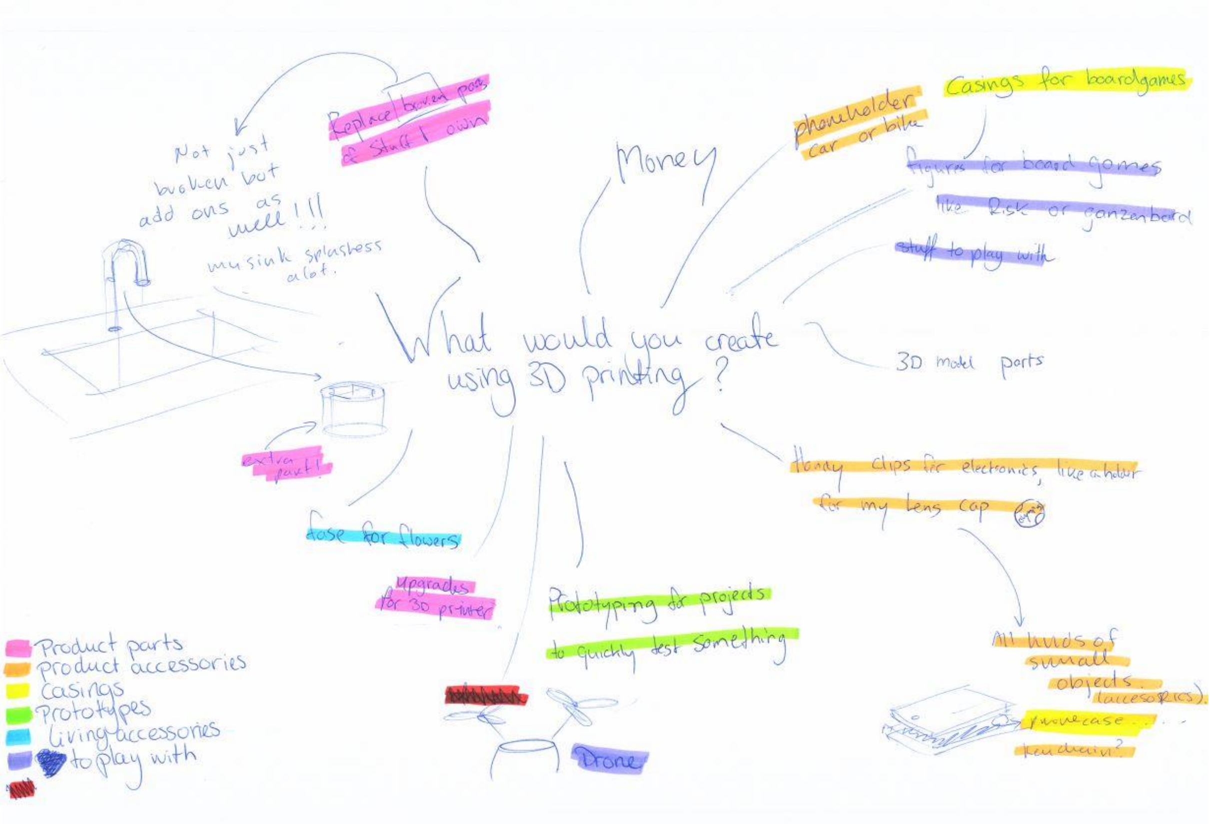
Holes	
Boredom	40%
Disgust	33%

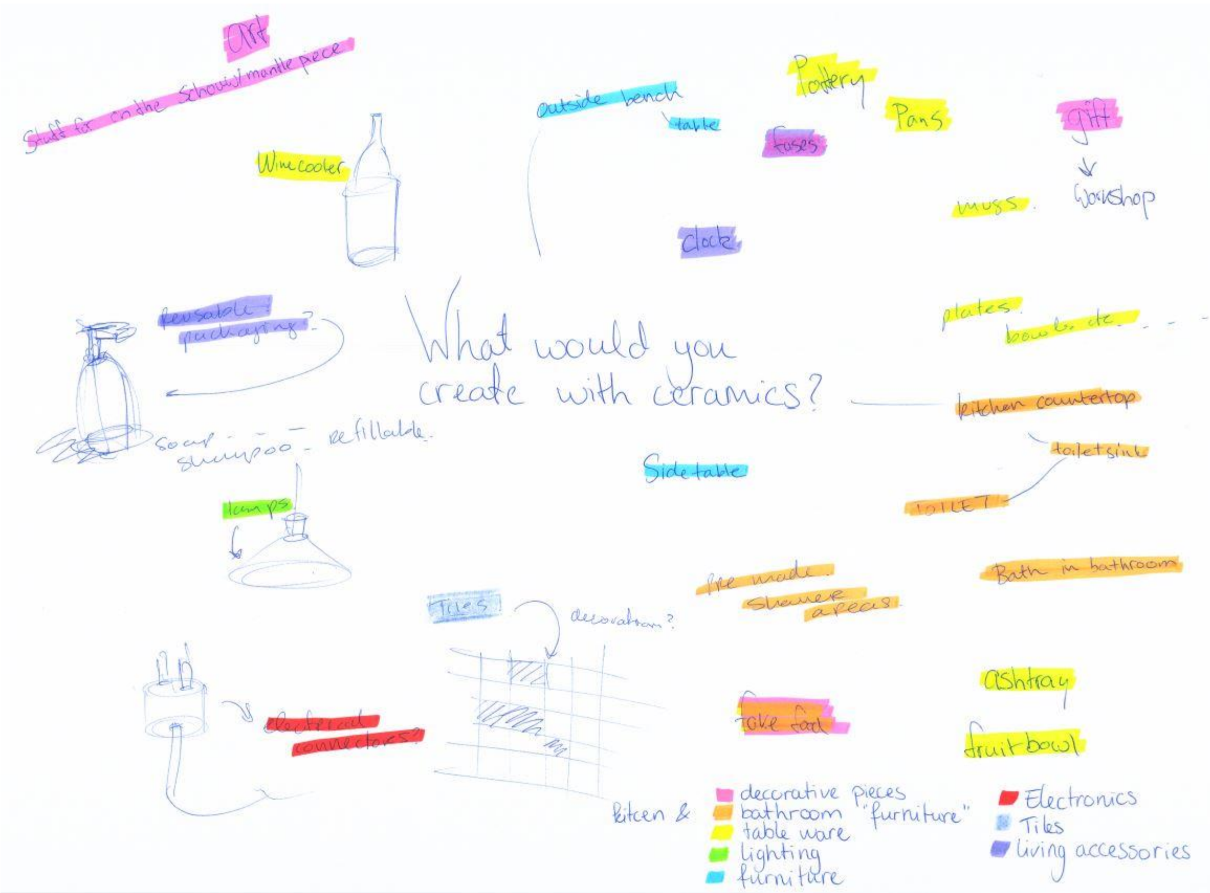
Straight lines	
Boredom	60%
Comfort	33%

Spikes	
Boredom	67%
Disapproval	33%

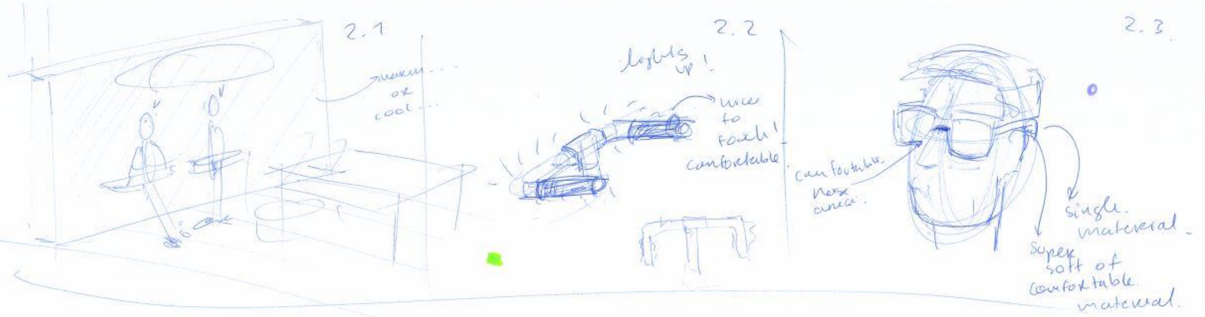
Appendix Q: Ideation scans

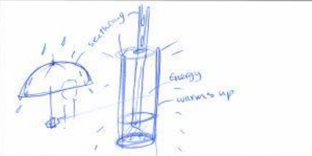
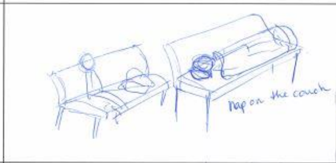
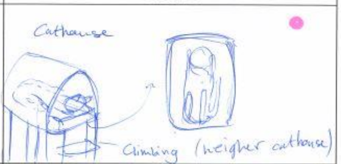
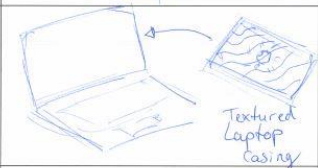
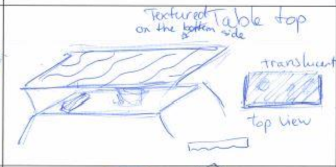
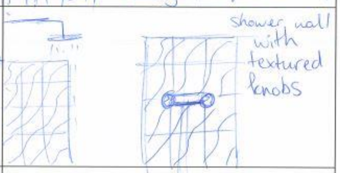
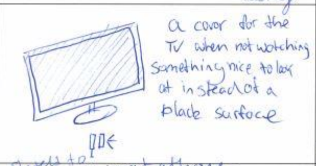
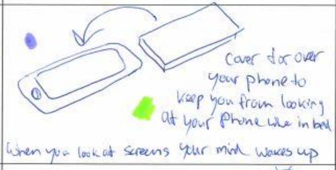
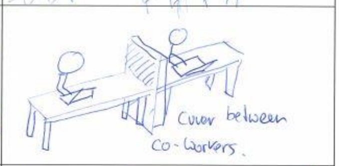
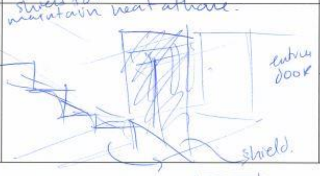
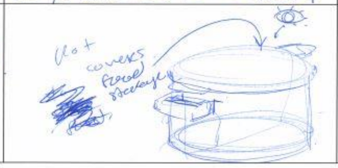
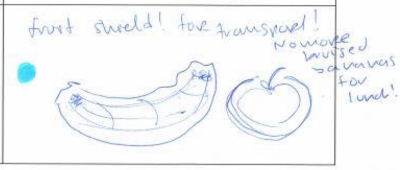


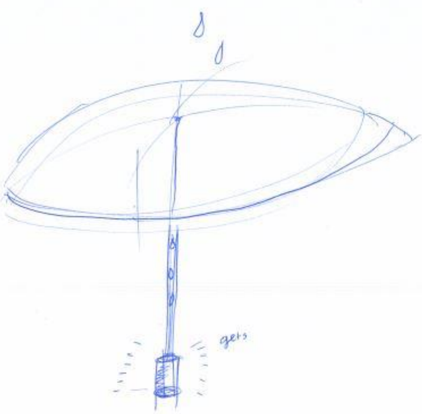


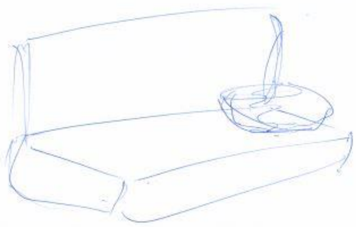

Art
outside bench
table
Pottery
Pans
gift
Workshop
mugs
Wine cooler
clock
What would you create with ceramics?
plates
bowls etc
kitchen countertop
refillable
toilet sink
Sidetable
TOILET
lamps
pre made shower areas
Bath in bathroom
Tiles
decoration?
ashtray
fake food
electrical connectors?
fruit bowl
decorative pieces
kitchen & bathroom "furniture"
table ware
lighting
furniture
Electronics
Tiles
living accessories

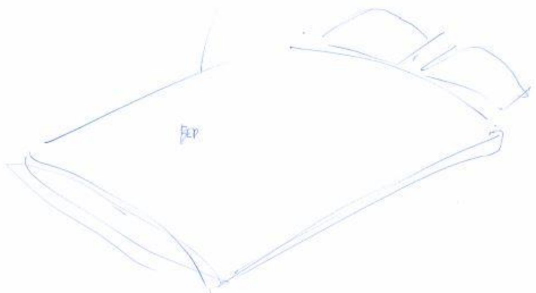
Create a product which	Comes in contact with light Is made from a translucent & tactually pleasing material		
	Idea 1	Idea 2	Idea 3
Participant 1	Shelters baby from direct sunlight but is fun to touch Baby	Lamp that emits a fire camp-like light for a nice atmosphere inside When playing cool games with beer	a soft lamp to take with you when going to the bathroom in the night. you want to stay sleepy so not a lot of light zzzz Portable
Participant 2	2.1 office window.	2.2 bike handle.	2.3 super comfortable sunglasses?
Participant 3	Bright to dim light adjustable lamp by touch	hammock When it is super hot cool extra warm on colder but nice days	less translucent for shadow translucent
Participant 4	Textured room divider or window with textured handles	Long earrings watch casing with textures that play with light	Textured candle holder



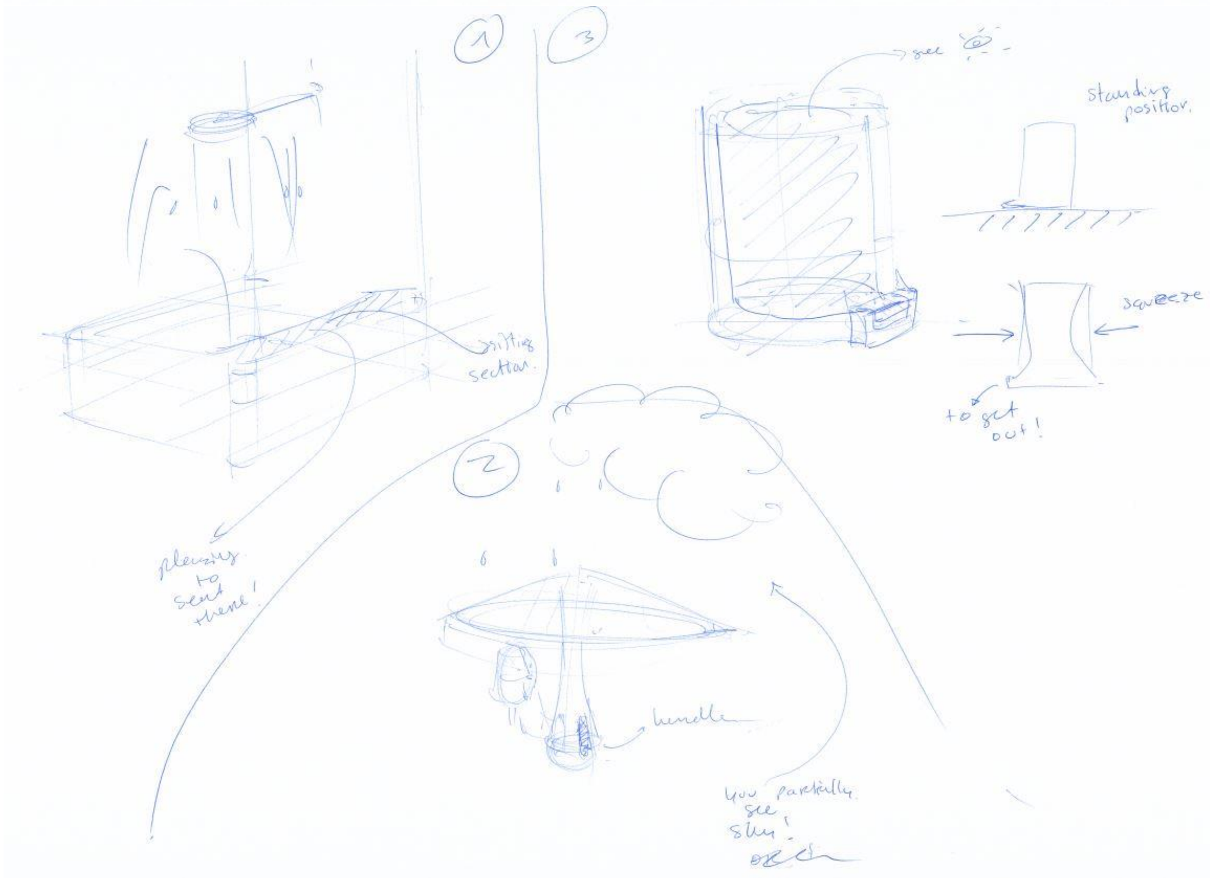
Create a product which	Covers, divides or shields Is made from a translucent & tactually pleasing material		
	Idea 1	Idea 2	Idea 3
Participant 1			
Participant 2			
Participant 3			
Participant 4			



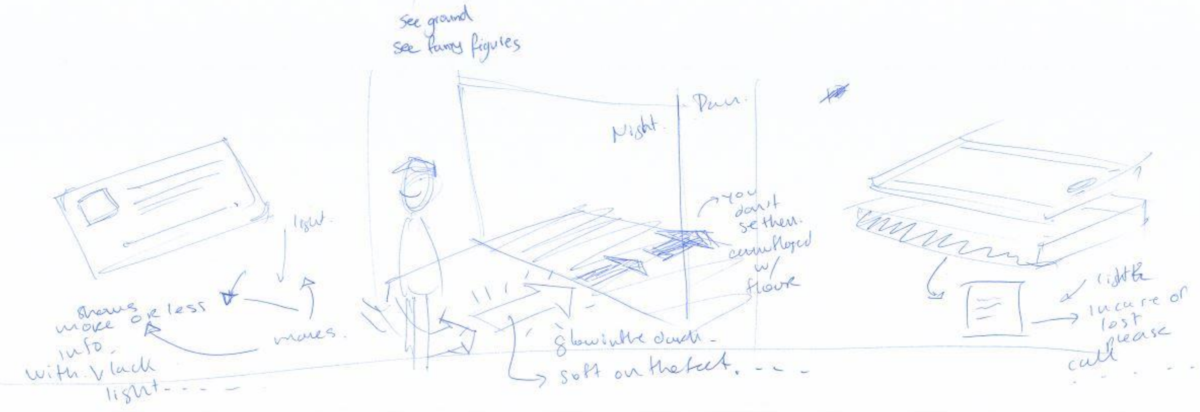


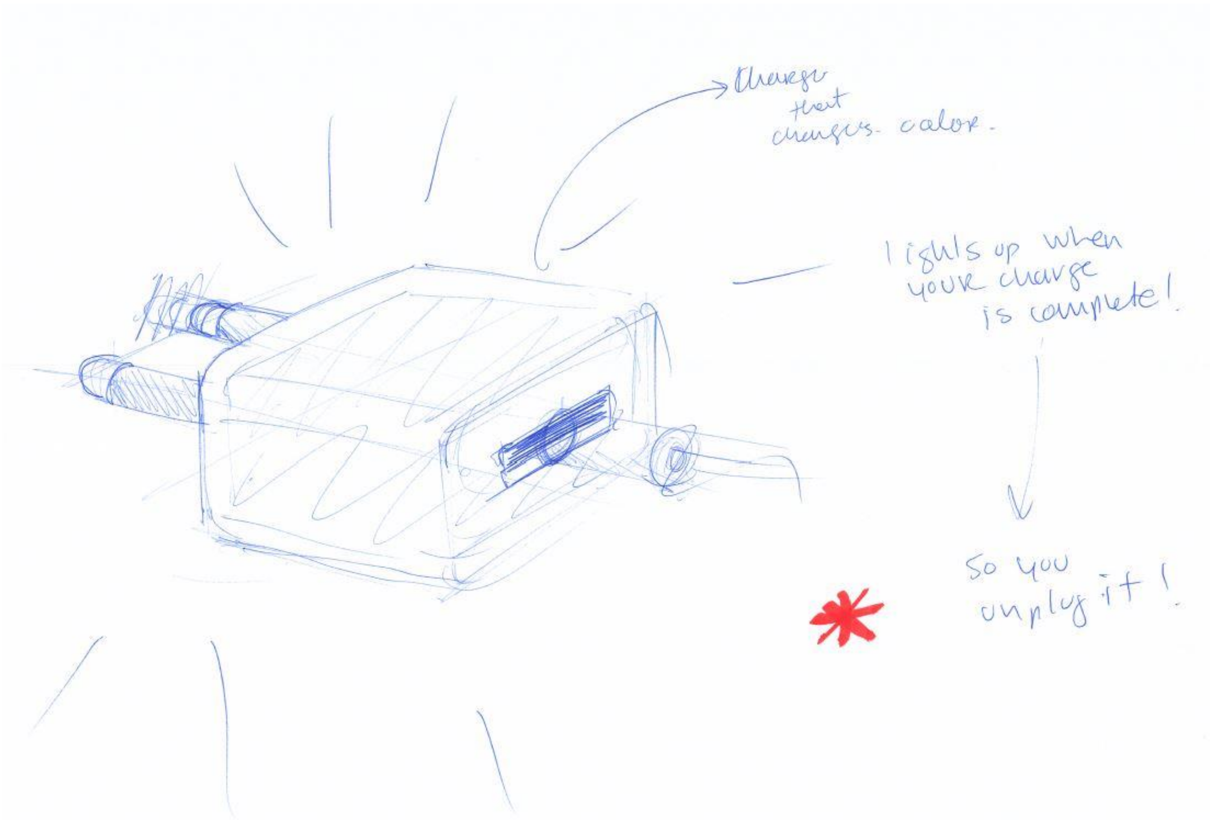


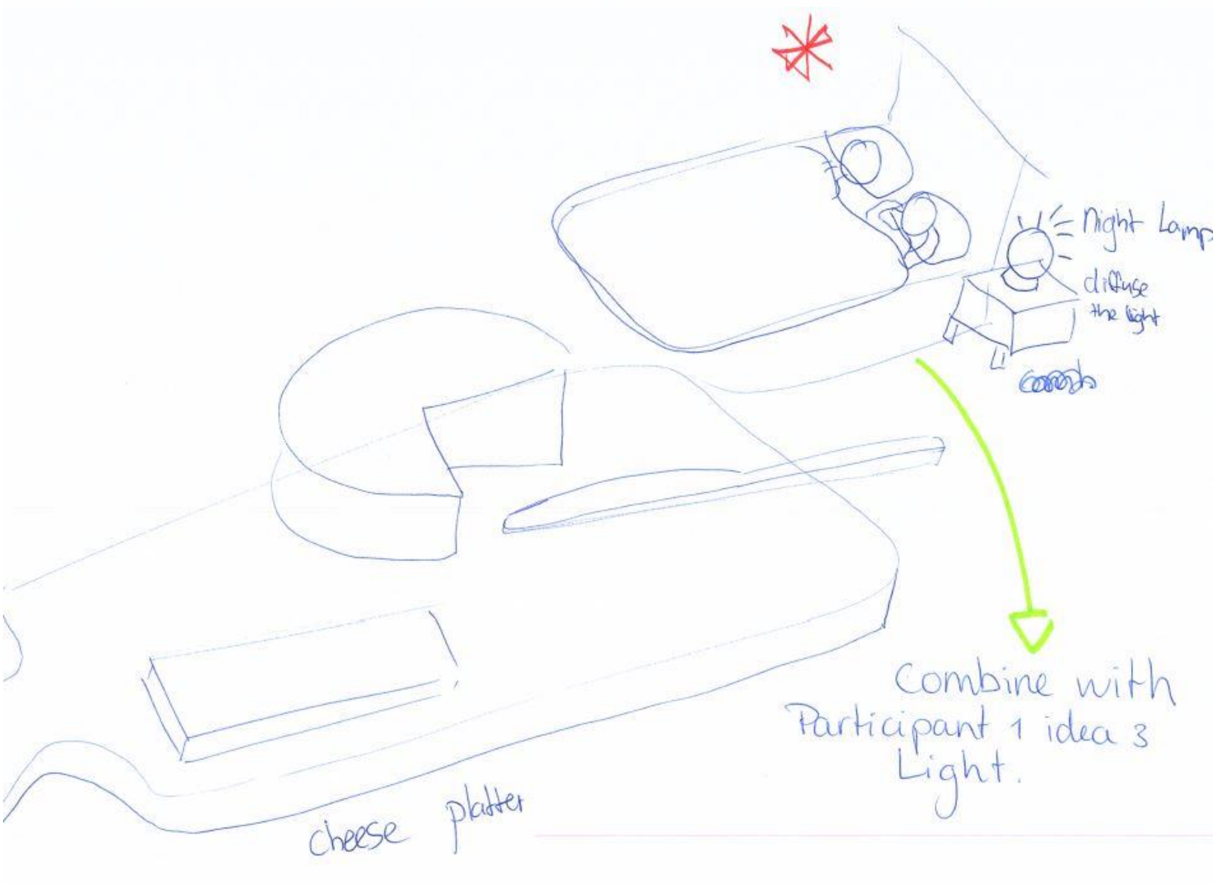
Create a product which	Comes in contact with liquids Is made from a translucent & tactually pleasing material		
	Idea 1	Idea 2	Idea 3
Participant 1	shower mat? shower or bathing area?	umbrella.	Soap containers
Participant 2	waterbottle, happy bottle	hotwater, tea, extra nice to hold	water, translucent
Participant 3	cups	Textured, Thea Kettle with cups	Bottom view, waterfall shower with lights and texture, And textured knobs
Participant 4	Baby bottle, extra comfy	Beautiful cat	Something to throw in the Pool to dive up

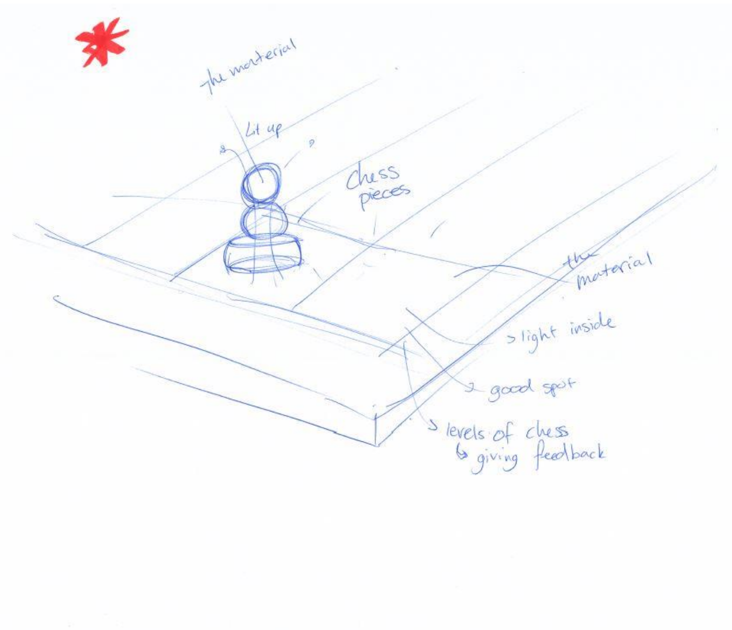


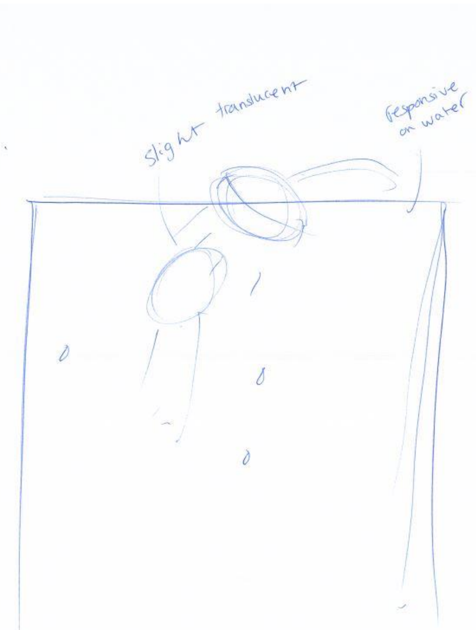
Create a product which	Has a hidden message or feature (aesthetically or functionally) Is made from a translucent & tactually pleasing material		
	Idea 1	Idea 2	Idea 3
Participant 1	cup	cup HALO HELLO	Jewellery wearable Hello
Participant 2	as a gift → add emotional value Best dad in the world So the message is not alway there ↓ more meaning/reminder	Sometimes when you are inside, you don't know if the temperature outside is comfy a window that lets you know when temperature outside is nice	a necklace that shows different portraits of loved ones based on the temperature 15° John 20° Sarah 25° mike 30° grandpa
Participant 3	3.1 ID card . . .	3.2 light path. for kids to go to the bathroom at night	3.3 phone case . . . with name . . . and extra number.
Participant 4	bike kid elongated window	phonecase USED FOR 10 MIN message about usage	tactile window HOSPITAL messages < jokes / happy message




charger that changes color.
lights up when your charge is complete!
so you unplug it!


Night Lamp
diffuse the light
Combine with Participant 1 idea 3 Light.
cheese platter


the material
Lit up
chess pieces
the material
> light inside
> good spot
> levels of chess
↳ giving feedback


slight translucent
responsive on water


Thee Kettle

Appendix R: Ideation

The results of round 1 were clustered creating lists of object types.
When asking the question: What would you create using 3D printing? it was found that people would create:

- Product parts
- Product accessories
- Casings
- Prototypes
- Living accessories
- Objects to play with

When asking the question: What would you create with ceramics? it was found that people would create:

- Decorative pieces
- Table ware
- Lighting
- Kitchen & bathroom “furniture”
- Furniture
- Electronics casings
- Tiles
- Living accessories

When asking the question: What do you touch often in you daily life? it was found that people touch:

- Items with hands
- Items with multiple body parts including hands
- Living beings or parts of living beings
- Substances
- Items which are worn on the body
- Items with complete or almost complete body
- Materials

The items which are touched often by hands are the focus of this research. These items can be divided into:

- Electronics
- Handles
- Controls and switches
- Table ware
- Games
- Stationary
- Cards, keys and money
- Vehicles or modes of transportation
- Packaging
- Table tops & counter tops

During the second round ideas were created. These ideas can be divided into product directions. The directions from each design challenge are listed below.
Light

- Lamps
- Walls / windows
- Wearables
- Mode or transportation handles
- Outside furniture

Liquids

- Bathroom furniture
- Cups, bottles and containers
- Umbrella
- Pool games

Cover, shield or divide

- Product casings
- Walls / windows
- Umbrella
- Shelters
- Packaging
- Table tops

Hidden feature activated by

- Glow in the dark
- Removing something
- Reflections / light
- Temperature
- Augmented reality / touch
- Liquids

Five ideas were formulated based on the material experience vision, the takeaways from the brainstorm and the methods of unveiling hidden messages and emphasizing translucency.

Idea 1
Tea set
This concept emphasizes the translucency of the material using liquids. The tea pot and cups are translucent, so when poring tea into the cups the tea can be seen flowing out of the pot and filling the cups.
This concept also includes tactile stimulation by having pleasantly textured exteriors based on the research executed in chapter 5.
Both the tea pot and the tea cups have hidden features. The tea pot has embossed or debossed textured on the inside which play with the liquid. So, they are not visible when the pot is empty but when filled they become visible. The tea cups have dual textured walls. Meaning, a pleasant texture on the outside of the cups and a hidden texture on the inside of the cups. These textures will complement each other and create one texture when unveiled through light or tea.

Idea 2
Chess game
This concept emphasises the translucency of the material using light. The chess pieces are hollow and contain LED's which are not visible when the pieces are not placed on the board. When the pieces are placed on the chess board they are turned on, lighting up the pieces showcasing the translucency of the material. Two colours are used to communicate which pieces belong to which player.
This concept also includes tactile stimulation by having pleasantly textured exteriors as is the case for concept 1.

The chess pieces also contain a hidden feature. The pieces have a minimalistic design from the outside. However, each piece contains an internal structure which becomes visible when the LED's are lit. This internal structure indicates and clarifies what kind of piece it is.

Idea 3
Fast charging charger
This concept emphasizes the translucency of the material using light. The casing of the fast charging charger is made from the material. The inside of the casing contains hidden LED's which turn on when the charger is plugged into the socket, revealing the translucency of the material.
This concept also includes tactile stimulation by having a pleasantly textured exterior as is the case for concept 1&2.
The hidden feature in the charger is functional information. When the charger is plugged into the socket the lit up LED's inside the charger casing will unveil time indicators. These indicators communicate how long it will take to charge the device. With time, the LED's will turn off one by one hiding the time indicators. Eventually all LED's are turned off indicating that the device is charged completely.

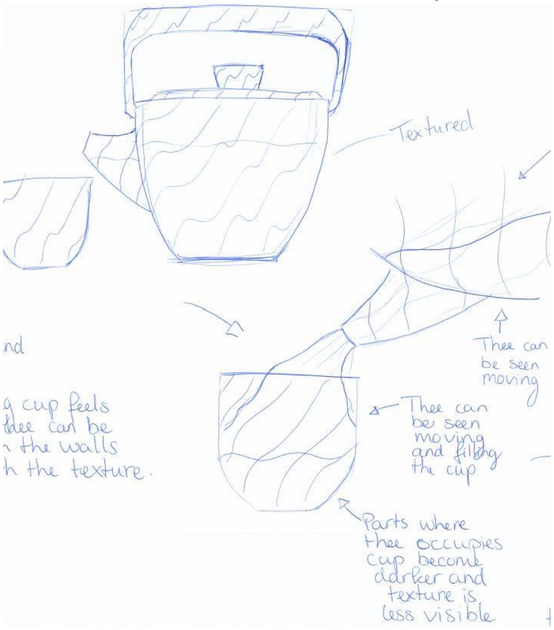
Idea 4
Waterfall shower
This concept emphasizes the translucency of the material using light and liquids. The knobs of the shower are hollow and contain LED's which are turned on when the shower is turned on, showcasing the translucency of the material. The translucency of the shower head is emphasized by the water which is running over the surface. When standing underneath the shower head the water can be seen flowing and playing with the translucency of the material.
This concept also includes tactile stimulation by having pleasantly textured exteriors as is the case for the other concepts.
The hidden feature for this concept is functional information. When the shower is turned off this information is hidden but when the shower is turned on the LED's light up and temperature information visualised on the inside of one of the knobs becomes visible.

Idea 5
Carrying wake up light
This concept emphasizes the translucency of the material using light. The lampshade is made from the material and is hollow. It contains a lightbulb which is turned on when the lamp is touched or when the alarm goes off, showcasing the translucency of the material.
This concept also includes tactile stimulation by having a pleasantly textured exterior as is the case for the other concepts. The lamp is turned on by touch but it can also be lifted from its base station and carried to a desired location making pleasant tactility of great importance.
The hidden feature of this concept is an hidden internal structure. The internal structure becomes visible when the alarm goes off and the lamp turns on or when the lamp is touched. The internal structure will be a calming shape complementing the external surface texture.

These ideas can be rewritten into design directions.

Design direction 1

Design direction 1 is to design an object which plays with the flow and movement of liquids. These dynamic liquids will unveil the hidden feature, when using the object. The design direction is divided into different elements. Functional, performative and sensorial.



Functional

The function of the material is to provide information about the liquid. Being the amount, the flow, the colour, etc..

The hidden feature can be functional indicating, for example, the exact quantity of the liquid. But it can also be purely aesthetic.

Performative

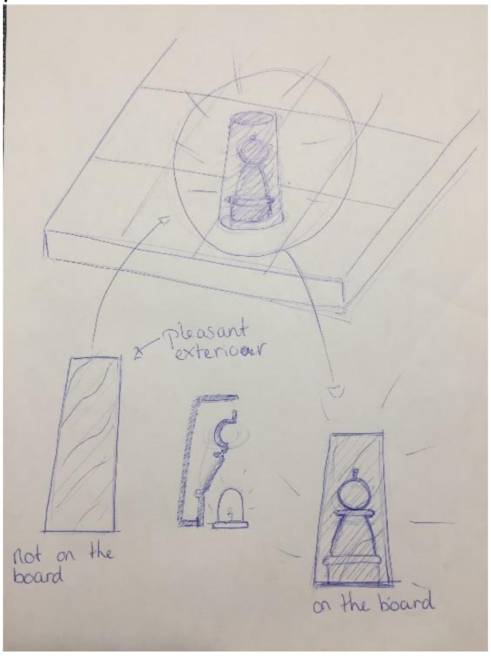
This design direction encourages the user to move the object, moving the liquid around inside. The move should be functional as well as fun, making sure that the object is always moved instead of only ones or twice when it is still new.

Sensorial

The translucency of the material is emphasized by a liquid and the tactual pleasantness is created by implementing digitally modified surface textures.

Design direction 2

Design direction 2 is to design initially identical looking objects which become distinguishable when the hidden feature is unveiled. The design direction is divided into different elements. Functional, performative and sensorial.



Functional

The function of the material is to communicate what the difference is between the initially identical looking object / parts. The difference between objects / parts is communicated by unveiling the hidden feature, making the hidden feature functional.

Performative

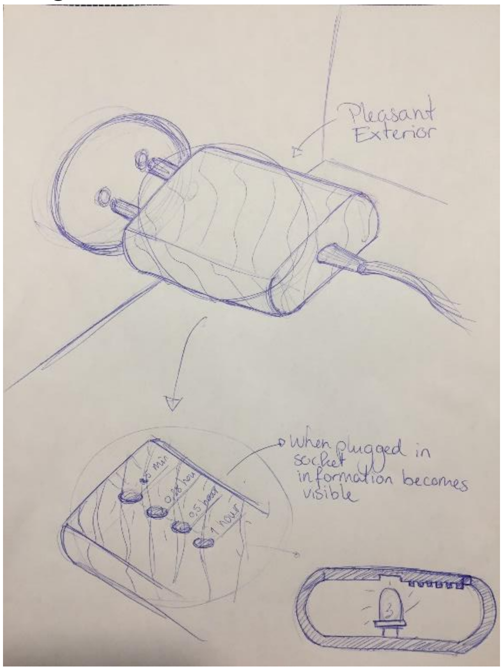
The performative actions are dependent on how the translucency gets emphasized. So, can be:
Moving object so liquid moves around
Moving object so substance moves around
Turning light on by moving, touching, stroking, pushing, etc.
Moving object so it is hit by natural lighting
Moving object so it will cover other objects

Sensorial

The translucency of the material can be emphasized in several different ways:
By light
By liquids
By substances
By covering something
The tactual pleasantness is created by implementing digitally modified surface textures.

Design direction 3

Design direction 3 is to design a daily used object with functional information, initially hidden and unveiled using light. The functional information will be unveiled when the object is being used. The design direction is divided into different elements. Functional, performative and sensorial.



Functional
The function of the material is to provide information about for example, the product settings or product status. The product settings or product status are communicated by unveiling the hidden feature, making the hidden feature functional.

Performative
This design direction requires the user to touch, hold, move, stroke or push the object or parts of the object. By doing so the light inside is turned on unveiling the hidden feature.

Sensorial
The translucency of the material is emphasized by light and the tactual pleasantness is created by implementing digitally modified surface textures.

Together with the stakeholders design direction 2 was chosen. This direction was chosen because it was the most unique direction and it would give the opportunity to show, for example, multiple digitally modified surface textures or hidden features. Really showcasing the possibilities of the material in combination with the free form, high precision production method.

Appendix S: Concept development

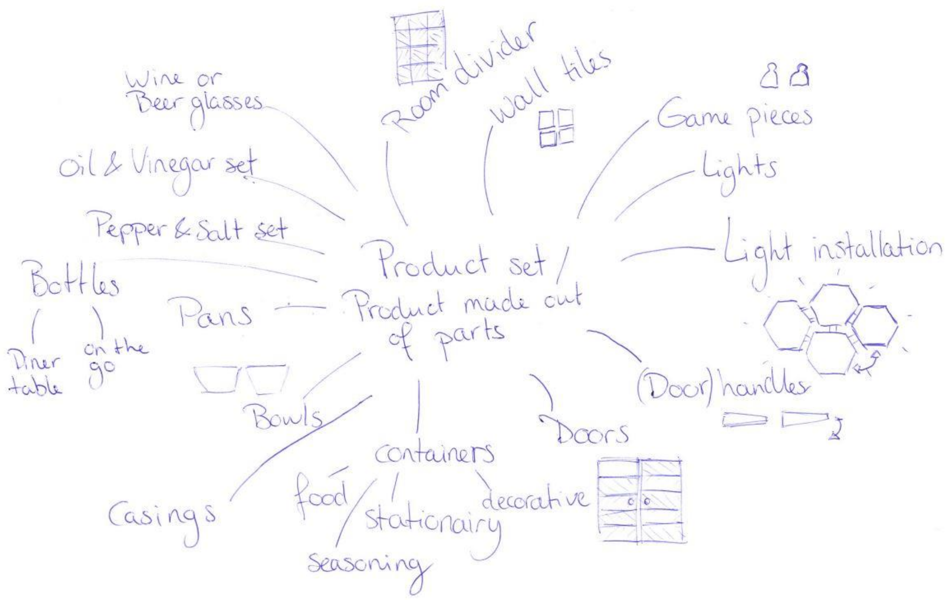
The concepts had to meet the following design constraints, formulated based on the material characteristics, material experience vision and design direction.

- It is easily printable with the Formlabs SLA printers.
- The concept is a product set or a product made out of several pieces. These pieces will initially look identical.
- The pieces should need, invite, encourage touch
- The pieces should allow for holding and movement
- The human-product interaction is frequent and includes long contact between human and product, making a pleasant tactile stimulation more important.
- The pieces should have a function which emphasises translucency
- The pieces should include a hidden feature which becomes visible when translucency is emphasised
- The translucency is emphasized by a performative action taken by the user. Is a tactual action and can be moving, holding, touching, pushing, stroking, etc.
- The concept makes use of the full potential of the 3D printing technique in combination with the material.

The design constraints have to be followed. Unlike design constraints, wishes do not have to be followed. A brainstorm takeaway was formulated into a wish.

- The hidden feature is functional information or a message with emotional value.

The concept development started with a quick brainstorm on possible product sets and products made out of several pieces.



Not all product sets fulfil the design constraints.
The ones that do not fulfil all constraints are:

Room divider
Does not fulfil constraints because a room divider does not have to be touched. The textures applied will invite to touch but this will be fun for a couple of times and after a while the room divider will not be touched anymore.
Furthermore, it does not allow for holding and movement. The room divider can be made out of separate parts which can be moved around. However, this moving around of parts should be made functional. Moving the parts around is fun but after a couple of times it will not be done anymore.
Lastly the room divider is fixed, making it harder to emphasize the translucency through a performative action like moving. The separate parts can be explored but seeing them together is more interesting. When wanting to see the hidden features of all pieces together, in frame the user has to move instead of the user moving the object.

Table top and wall tiles do not fulfil the constraints for the same reasons as room divider.

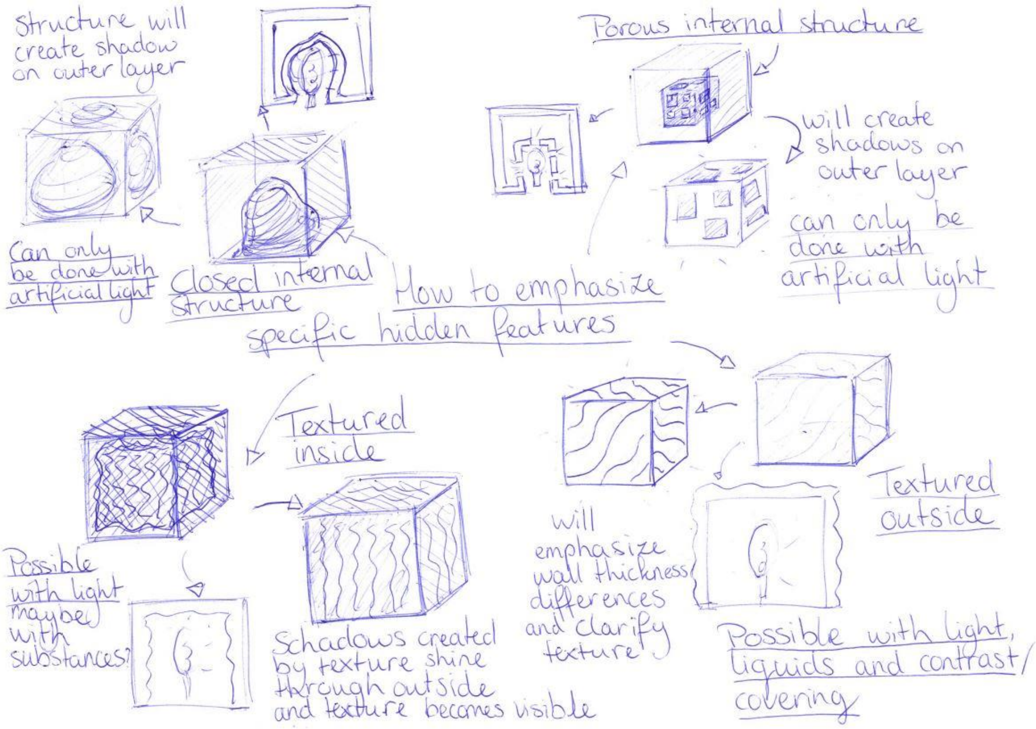
Casings
The casings will be developed to cover not to protect. The material has a relative high impact resistance but not high enough to be fit for protective casings.
The casings do fulfil the constraints but using a translucent material does not seem logical for this functionality. The cover would have as a function to make sure that the user does not get distracted by electronic devices. But the light of the screen will still shine through when using a translucent material with an inviting texture. Probably distracting the user even more. It will become an aesthetic looking light which when lit up communicates that you are getting messages.

There were also some product possibilities which do not fulfil the constraints perfectly but still good enough:
Door handles
A door handle is fixed to a door so it cannot move freely. However, it is not fixed since it can still rotate or move up and down. Still allowing for holding and movement.
Door handles are mostly covered by the users hand when using. When covering the handle the hidden feature that is being unveiled cannot be seen. So the hidden feature should probably we placed on a spot next, below or above the handle.

Doors
As is the case for the room divider, doors do not allow for holding and free movement. The door does allow for more movement than a room divider since it can be open and closed but it cannot be taken to another environment. The door can be made out of separate parts which can be moved around. However, this moving around of parts should be made functional. Moving the parts around is fun but after a couple of times it will not be done anymore.
Furthermore, doors themselves are often not touched. Only when the handle is incorporated in the door. But then still a big part of the door does not need to be touched. The textures are inviting and in the beginning people would want to touch the textures but after a couple of times the door will not be touched anymore. Creating a door from more pieces will allow for more movement and touch but as said before this moving around should have a functionality.
Lastly the door will be moved unveiling the hidden feature. If the hidden feature can be seen is however dependant on the environment on the location of the door since the door is fixed. It can be to dark not unveiling anything so this should be kept in mind when designing a door.

The product categories which were left were translated into some product ideas visualised in appendix T.

Some ideas are more feasible to actually work, to produce or are more interesting. To make sure that the ideas will actually work and can be produced all possible hidden structure types were listed in combination with how they can be unveiled.



Some uncertainty came up about the functionality of some of the ideas. It is not sure if the technique of closed internal structures can actually be unveiled using liquids or substances. Meaning it is unclear if the wine glass, salt and pepper shaker and oil and vinegar bottle ideas will work. Unfortunately there is no time to test this. It is however still super interesting so could be further researched in future research.

The container does not have a very interesting hidden feature. Furthermore, the texture on the outside will not get clarified because no light is used so this idea is not very exciting.

The door has pieces with a functionality but when placing the parts they will probably not get moved around often anymore. So big parts of the door will not be touched anymore after a while.

This leaves the:
Door handles
Chess game
Light installation
Table lamp

Appendix T: Idea scans