Quality analysis of high-pressure casted washbasins

Degree Thesis

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Sammandrag:

Produktionen av sanitetsporslin (toaletter, tvättställ och urinaler) i keramik har utvecklats snabbt och högtrycksgjutet som används vid Geberits fabrik i Ekenäs är modernt och ständigt under utveckling. Detta examensarbete handlar om kvalitetsproblem och defekter vid tillverkning av keramiska tvättställ. Det innehåller olika metoder för att kvantifiera, kategorisera och undersöka orsakerna till olika defekter. En litteraturgenomgång och en fördjupad beskrivning av tillverkningsprocessen utfördes för att skapa en grund, då tidigare forskning i ämnet är begränsad. En 3-månadersperiod tillbringades i fabriken med att genomföra experiment och undersöka gjut- och torkningsprocessen i gjuteriet. Undersökningarna omfattade tillverkningsprocessen från gjuteriet till kvalitetskontrollen, massaproduktion exkluderat, för att upprätthålla lämplig längd på analysen. Arbetet gjordes i samarbete med olika avdelningar på fabriken och diskussioner i form av dagliga möten fördes. Resultaten visade att luft- och temperaturförhållandena påverkar torkningshastigheten, vilket ökar risken för sprickbildning. Dessutom minskade produkter som avvisades på grund av dimensionsavvikelser då extern hantering utförd av robot infördes. Resultaten visar att prioritet och fokus ligger i att lösa kvalitetsfrågor relaterade till sprickbildning och dimensionsavvikelse. Dragna slutsatser visar att en noggrann uppföljning av parameterändringar och eventuell framtida utveckling av avformningsstödet kan förbättra kvaliteten.

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Abstract:

Production of sanitaryware (toilets, washbasin and urinals) in ceramic has developed rapidly and the high-pressure casting used at Geberit's factory in Ekenäs is high-tech and constantly under development. This degree thesis concerns the quality problems and defects in production of ceramic washbasins. It involves different methods to quantify, categorize and investigate the causes for different defects. A literature review and an in-dept description of the manufacturing process was done to lay a foundation as previous research on the subject is limited. A 3-month period was spent in the factory conducting experiments on the casting and drying process in the foundry to investigate impact factors. Investigations included the manufacturing process from the foundry to final inspection, excluding slip production to maintain suitable depth of analysis. Work was done in collaboration with different departments at the factory and discussions in the form of daily meetings were held. Results found that ambient conditions affect the drying rate, increasing risk of cracking. Moreover, additional external handling performed by robots in the production decreased products rejected due to dimensional deviation. Results show that priority and focus lie in solving quality issues related to cracking and dimensional deviation. Drawn conclusions show that diligent follow up of parameter changes and possible future development to the de-moulding support can improve quality.

Keywords:	Geberit Productions, Ceramics, Sanitaryware, High-pressure, Casting, Quality, Defects, Washbasin
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FOREWORD

Firstly, I would like to thank my supervisor Mathew Vihtonen for the provided guidance, support, and eager ideas during the entirety of the writing process. I thank Geberit Production Oy in Ekenäs for the opportunity and cooperation in making this degree thesis. It has been an eye-opening journey that has taught me a lot about myself and the field as an engineer in sanitaryware production.

I would also like to reach out a special thanks to Ann-Charlott Nyberg and Timo Malmi at Geberit for mentorship, guidance and discussions throughout the process as well as thank Johan Pihlström and Robert Kallström for experience, support, and endless assistance in the foundry. Thanks to Leif Öhman, Tove Lagerström, Dennis Brandt, Anu Arhippainen and Kimmo Sironen for assisting in different experiments.

Lastly, I wish to thank my family, friends, and girlfriend for believing in me, encouraging me and keeping me on track with my goals.

Robin

1 INTRODUCTION

Geberit Production Oy based in Tammisaari; Finland is a 50-year-old ceramics factory that was acquired by the Geberit group in 2015. The factory produces sanitary porcelain under the brands IDO, IFÖ, Porsgrund Bad and Geberit. The utilized high-pressure casting is high-tech and leading in the technology but as a result of recent internal quality requirements growing stricter a problem with quality in the washbasins have occurred. The purpose of the thesis is to alongside the factory's own efforts, study and evaluate the factors affecting the dimensional deviation and other defects in order to address the problem and ensure sufficient quality of the washbasins.

1.1 Issue

The issue of the degree thesis is to analyze and document the factors that impact the quality of high-pressure casted washbasins at Geberit's factory in Ekenäs, in collaboration with the technical department. It is also desired that the degree thesis would provide easy access to documented tests and their results when similar problems occur in the future.

The degree thesis is limited to the manufacturing process from casting, including mould design, until final inspection, including quality control. Slip parameters are discussed as they affect casting, however it does not include slip production and storage to any further extent. Focus within the thesis lies on the major problem of internal quality requirements growing stricter and the occurrence of dimensional deviation (warping/distortion) as well as cracking of the products. The majority of defects are discussed as certain solutions done in production can have a reaction in other defects occurring.

1.2 Relevance of the problem and relationship to existing knowledge

With multiple departments working on the ongoing project at Geberit's factory in Ekenäs the documentation and investigation of what affects the quality of washbasins is a relevant problem.

Expertise from Arcada’s courses manufacturing processes, fluid mechanics, product design and computer aided manufacturing is relevant knowledge that can be used when analyzing the process. Finite element analysis and data analysis is important when doing tests to ensure reliable results. Previously existing knowledge from the ceramic industry, a problem-solving mentality and interaction with different departments are to be implemented when assisting the factory in its’ own efforts to combat the quality challenges.

1.3 Objective

- Describe the process of high-pressure casting washbasins
- Collect and analyze relevant data for the process
- Propose and if possible, test a process improvement to ensure sufficient quality

2 LITERATURE REVIEW

2.1 Ceramics

Clay was an important building material in ancient Egypt, Assyria and Mesopotamia. By drying clay in the sun, clay bricks that could be used in construction were produced. However, the bricks would tend to dissolve into soft clay when water was re-introduced. It was only later that it was discovered that firing clay at high temperatures would initiate an irreversible hardness. Oven-like creations were used to make ceramic out of the clay by accomplishing a ceramic transformation. Ceramic, as a term, originates from ancient Greek and is derived from the words keramikos and keramos. Ceramics refer to solid articles formed from inorganic compounds, earthy raw materials and heat. The inorganic compounds commonly contain oxygen, silica, alkali metals and alkaline earth metals. Quartz and different types of oxides is the most common compounds. (Jylhä-Vuorio, 2003)

In 1960 Kingery, Bowen and Uhlmann defined ceramics as “the art and science of making and using solid articles which have as their essential component, and are composed in large part of, inorganic nonmetallic materials.” Their definition is wider than the previously mentioned keramos. According to Kingery, Bowen and Uhlmann the term ceramic should not only contain materials like pottery, porcelain, refractories, clay products, enamels, cements, and glass but also ferroelectrics, manufactured crystals and glass ceramics. As fabrication and production methods develop, their definition aims to be less restrictive. Furthermore, the definition include products which did not exist a few years ago and many that are yet to exist. (Kingery;Bowen;& Uhlmann, 1976)

Sanitaryware or sanitary porcelain is a division of ceramics that comprises of toilets, washbasins, bidets, and bathtubs. Sanitary stands for hygienic and clean, ware for product or object. Sanitary porcelain is often called vitreous china (VC) and means china clay has been used alongside the ball clay in the ceramic slip and the product has been fired at 1200 °C. (Ortonbath, 2017)

2.2 Raw materials and ceramic slip

Sanitary porcelain is produced by casting ceramic slips in moulds. A slip is an aqueous suspension, where the used raw material is dispersed into water. Sanitaryware contain mainly mineral mixes, with a few major components and many smaller ones. The raw materials used in sanitary porcelain can be divided into plastic and non-plastic raw materials. (SACMI, 2010) The ceramic slip is produced by first mixing the plastic raw materials with hot water, followed by the non-plastic materials. The properties of the slip can then be further manipulated with flocculants and de-flocculants to achieve desired viscosity, density, thixotropy and permeability. (Jylhä-Vuorio, 2003)

2.2.1 Plastic raw materials

The plastic raw materials are often a mix of clay materials. The bodies' plasticity is its' ability to withstand fracturing when external forces are applied. It is also the ability to preserve the new shape when external forces are removed. (SACMI, 2010) Furthermore, the plastic raw materials provide ductility and dry strength to the ceramic cast. The slip parameters can effectively be adjusted with the help of plastic raw materials as the addition of plastic raw materials slow down drying and reduce water absorption in the green stage. The most common plastic raw materials in the ceramic slip are ball-clay and kaolin. (Jylhä-Vuorio, 2003)

2.2.1.1 Kaolin

Kaolin is a term for primary and secondary clays, mainly consisting of the pure mineral kaolinite and 1-2% of other minerals. Another name for kaolin is china clay, which comes from its' origin. Until the 18th century kaolin was unknown to the Europeans and the best porcelain was produced in China, by using equal parts of kaolin and pe-tun-tse (similar to pegmatite). Kaolin, when processed into a raw material used in ceramic slips is a white, light and easily dusting powder. Its' melting point is 1750-1770°C, at temperatures above 1100°C the majority of kaolin in the slip is converted into mullite. The addition of kaolin to the ceramic slip increase the melting point and add whiteness to the fired product. Kaolin also makes for a more fluid slip and reduced casting time when compared to strictly ball clay slip. (Jylhä-Vuorio, 2003)

2.2.1.2 Ball-clay

Ball clays are the basic raw materials in the ceramic industry, containing kaolinite and secondary clays with varying amounts of organic and inorganic contaminants depending on their origin. Kaolinite is the main mineral in ball clay; however, it can also contain montmorillonite, halloysite, quartz and illite. The melting point of ball clays range between 1200-1300°C, the burnt color is white around 1200°C but quickly darkens as they melt. Ball clays provide the ceramic product with its' plasticity, toughness and dry strength. Ball clays alone cannot be used in ceramic slips as they are too plastic and slippery. The plasticity is achieved through water absorption. Large amounts of absorbed water lead to a larger drying shrinkage and can result in cracking or warping. Due to their nature ball clays vary in quality and it is therefore recommended to use two or three different qualities in the same slip to achieve target values. (Jylhä-Vuorio, 2003)

In the Ekenäs factory different ball clays are used to stabilize the fluctuation in composition from raw material changes.

2.2.2 Non-plastic raw materials

Feldspar minerals, quartz, bauxite flint and chamottes are the non-plastic raw materials, even called hard raw materials, used in sanitaryware. (SACMI, 2010)These materials are the coarser part of the slip and are used to thin out an excessively plastic slip. The addition of non-plastic raw materials allows for an easier escape of water from the slip. Thus, leading to faster drying rates, however the downside is more water absorption in the green stage. When up to a certain amount of non-plastic raw material is added to the slip it will reduce drying shrinkage and improve processability. If above 50% of the slip contains non-plastic raw materials the drying strength will suffer. (Jylhä-Vuorio, 2003)

2.2.2.1 Feldspar

Feldspars are the most common minerals of crystallized rock and the second most important raw material used in the ceramic industry, after clay. There are four common types of pure feldspar:

- Potassium feldspar
- Sodium feldspar
- Lithium feldspar
- Calcium feldspar

Potassium feldspar is the most common feldspar, followed by sodium feldspar. The two possess similar characteristics; however, potassium feldspar has a wider temperature range for firing. Potassium feldspar commonly contain equal amounts of potassium and sodium while sodium feldspar can contain potassium as well. Potassium feldspar has a melting temperature of 1320°C and sodium feldspar has a melting temperature of 1120°C. However, the two form a eutectic mixture when 65% potassium feldspar and 35% sodium feldspar is mixed, the melting temperature is then 1070°C, which is lower than any of the individual melting points. (Jylhä-Vuorio, 2003)

Feldspar added to the ceramic slip act as fluxes by lowering the melting point. During firing the feldspathic minerals interact with the free silicon and clay minerals to form mullite. In addition, feldspar also reduce the porosity which lead to a more compact ceramic body. The hard and non-plastic feldspar also reduce the plasticity of the unfired product. (SACMI, 2010)

Feldspars are not commonly found in their pure form and usually found mixed with quartz and mica, making pegmatite. Pegmatite is similar to previously mentioned pe-tun-tse that was a mix of feldspar and quartz used in China. (Jylhä-Vuorio, 2003)
The pegmatite used in Ekenäs has been cleaned from mica and iron contaminates. It contains 26% potassium feldspar, 36% sodium feldspar and 2% calcium feldspar for a total of 64% feldspar and 36% quartz.

2.2.2.2 Silica (Quartz)

Silica or more commonly referred to as quartz, in its’ common element is a crystal. The quartz crystal is colorless, transparent and very hard. Due to its’ hard nature the quartz used in the ceramic industry is usually separated from pegmatite when processing feldspar. The separated quartz sand is easier to grind compared to hard quartz stone. Pure quartz can also be obtained from sea sand. Quartz acts as a skeleton, gives the ceramic slip its’ structure and thins out a too plastic slip. The addition of quartz raise the melting temperature of the ceramic slip. Quartz lowers the drying shrinkage of the ceramic body but on the other hand it also lowers its’ dry strength. (Jylhä-Vuorio, 2003)

According to Sacmi 2012 quartz is also used in ceramic slips to:

- reduce body plasticity
- increase thermal expansion coefficient
- increase body vitrification temperature
- form mullite during firing

Mullite and residual quartz form the load-bearing structure of the ceramic body and hinder deformation during firing. (SACMI, 2010)

Quartz have crystal structure changes as temperature rises and decreases. The critical temperature for this is 573°C when quartz α change to quartz β. At this stage the quartz expands 2% due to a change of angles within the tetrahedral structures of the molecules. A total of 3% expansion happens between 0°C and 573°C. The same effect is reversible when cooling down the ceramic body. (Jylhä-Vuorio, 2003)

2.2.3 Slip parameters

2.2.3.1 Viscosity

Viscosity is the opposite of fluidity which means the ease of flow. Viscosity is described as the opposition of flow - the resistance of a fluid to change shape or move. Therefore, viscosity determines how easily a fluid material can be transported in pipelines and when injection moulding as an example. (Britannica, T. Editors of Encyclopaedia, 2022)

At Geberit in Ekenäs viscosity can measured with a pipe viscometer or a rheometer. The pipe viscometer measures apparent viscosity by manually timing the flow of slip from a pipe. The rheometer uses a rotating cylinder to measure two different data-points of the slip. The difference between these values is then used to produce a reading for both viscosity and thixotropy.

2.2.3.2 Thixotropy

Thixotropy is explained as the behaviour of gel like materials that liquefy when they are shaken, stirred, or disturbed and then reset when left untouched. The surface of certain paint can show thixotropy, the paint flows freely when stirred but forms gel on the surface when still. Thixotropy is present quicksand, a mixture of water and sand – where the presence of certain clays produce thixotropic behaviour. (Britannica, T. Editors of Encyclopaedia, 2016)

The cause of thixotropy is a decrease in viscosity when a fluid is moving and a return of viscosity when still. When still the particles within the slip are attracted to each other and form flocs, however the force is weak enough to be disrupted by external stress, like stirring. (Mewis & Wagner, 2009)

Thixotropy in the slip in Ekenäs is measured using a Gallenkamp torsion viscometer but can also be measured using the rheometer. The Gallenkamp torsion viscometer is an instrument developed for the ceramic industry, however the MCR rheometer is preferred at Geberit.

2.2.3.3 Permeability

Permeability has the standard unit of Darcy, which is equivalent to one cm^3 of liquid per second that passes through a one centimetre thick and a cross section of one square centimetre at atmospheric pressure. This represents the porous material's capacity to transmit a fluid at specified viscosity and pressure. (Britannica, T. Editors of Encyclopaedia, 2018)

Permeability in ceramics represents the rate at which water exits the slip and this directly affects the casting rate of the slip. Higher permeability is achieved in flocculated slips, however as discussed earlier these require more water. Adding slight amount of deflocculants to not compromise thixotropy or casting time is therefore recommended. (Worrall, 1986)

In Ekenäs the permeability of the slip is measured doing a baroid test. The slip is pressed through a filter at 6bar for 30 minutes, this forms a cake in the chamber. The permeability is then calculated from the volume of the cake and filtered water.

2.2.3.4 Density

Density, a materials mass per unit volume, is defined as $d = \frac{m}{V}$, where d is density, m is mass and V is volume. The common unit for density is grams per cubic centimeter, as an example the density of water is $1\left(\frac{g}{cm^3}\right)$ (Britannica, T. Editors of Encyclopaedia, 2021)

At Geberit's factory in Ekenäs density is measured as liter-weight, which simply means grams per liter, $\frac{g}{L} = \frac{g}{dm^3}$. This is done through a laboratory test where a 1 litre cylinder is filled with slip, a lid with a hole is pressed onto the cylinder to remove any excess slip and ensures exactly 1 liter is used for the measurement. The cylinder is then weighed, and the weight of the cylinder is then subtracted from the total – giving the gram per liter reading. It is desired to have a slip with high density without compromising flow.

2.2.3.5 Porosity

The porosity is the percentage of void in a material as seen in figure 1. Porosity is defined as the ratio (n) for pore volume over total volume.

Equation 1

$$n = \frac{V_{pore}}{V_{total}}$$

(Wisconsin Geological and Natural History Survey, 2020)

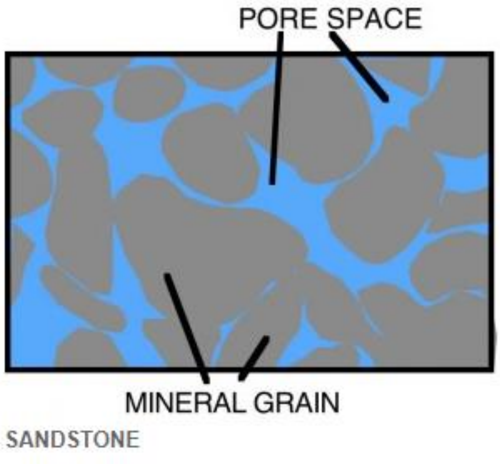

Figure 1: Porosity (Source Wisconsin Geological and Natural History Survey)

When the ceramic piece is fired in the kiln it goes through a process called sintering. Sintering is a process where porosity is removed, and the piece forms a solid mass through changes in the microstructure. In figure 2 one can see example of the sintering process, where the void between the particles melts together and is removed. (ceramic.org, 2019)

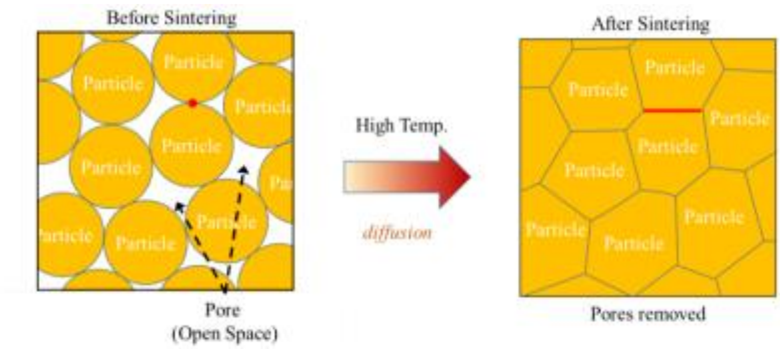

Figure 2: Sintering (Source ceramic.org)

The desired porosity in sanitaryware is below 0.5% and represent the total amount of pores compared to the volume of the sanitaryware body. (Jylhä-Vuorio, 2003)

In Ekenäs the porosity is measured on fired but unglazed test pieces according to EN-997 standards. The test pieces are dried and weighed and then put in a pot of water for 20 hours. Another weight measurement is then taken after wiping the pieces with a cloth.

Comparing the original weight with the absorbed weight then allows for calculation of apparent porosity with the formula $\phi = \frac{m_1 - m_0}{m_0} \cdot 100\%$ (Palomäki, 2020).

2.2.3.6 Drying rate

Drying rate is the speed at which the desired moisture level of the ceramic piece is reached. A slow drying rate means the process time is increased or the ceramic is too wet, a faster drying rate can lead to cracking during the drying phase, these defects are further discussed in the casting defects segment. It is therefore important the drying rate is measured and optimized accordingly.

When measuring drying rate at Geberit a mould is filled with slip at a set casting time. The remaining slip is then emptied, and the then glossy piece is inspected. The drying rate is measured as the time it takes for the glossy piece to turn completely matte.

According to Wagner Jr., Mount and Giles Jr. study on polymer pellets it was found that drying rate is affected by surrounding air temperature and air dew point. A lower air de point in turn lowers the air moisture content and would lead to water migrating from the body more quickly. Furthermore, the total weight percent of moisture in the pellets had an impact on the drying rate. Air flow around the pellets was a critical factor when removing wet air, therefore increasing the drying rate. It was found that materials that absorb moisture from the air do so until equilibrium is reached. (Wagner Jr.;Mount;& Giles Jr., 2013)

To investigate the effect of drying rates at the foundry and the drying tunnels, ambient temperature and moisture levels are to be investigated and compared to overall casting results. It would be expected that lower ambient moisture allows for faster drying in the foundry, meaning dryer goods go into the drying tunnel.

2.2.3.7 Casting speed/thickness

The casting speed or casting thickness of the ceramic slip is the rate at which the walls of the ceramic body forms within the mould. This measurement is important as certain thicknesses must be achieved in order for the fragile ceramic body to withstand further handling and possible internal forces that occur from casting. (Palomäki, 2020)

In Ekenäs the casting thickness is measured by weighing a cut out piece of a specific area from flat piece of ceramic. The mass of the cut-out piece is then the casting thickness. To easily measure casting thickness in production a ultrasonic measurement gauge is used.

2.2.3.8 Flocculants and de-flocculants

Flocculants are substances that alter the ceramic slip and make the clay particles adhere to each other in order to form card-like structures. This is advantageous in ceramic manufacturing as it prevents sedimentation of the ceramic slip. Examples of flocculants are calcium sulphate, magnesium sulphate and acetic acid. (Jylhä-Vuorio, 2003) At the factory in Ekenäs flocculants are rarely needed when producing ceramic slip, however gypsum is used as a flocculant if needed.

De-flocculants work in the opposite manner of flocculants and cause the clay particles to repel each other. The addition of de-flocculants allows for a flowing ceramic slip even with low amounts of water. Water glass(sodium silicate) and soda ash(sodium carbonate) are examples of de-flocculants used in ceramic manufacturing. (Jylhä-Vuorio, 2003) De-flocculants are used in Ekenäs to achieve desired slip properties.

2.3 Casting, Manufacturing process

Casting is a manufacturing process in which liquefied material is poured into a cavity of a mould. The liquid material is then allowed to solidify. After hardening and solidification the piece is removed from the mould for secondary operations or direct use as a final product. Thermal treatment or material removal are examples of secondary operations. Molten metal is the most widely used and common material used in casting. However, ceramics and polymers can also be used as material in the casting process. Depending on the material and desired outcome the casting process can be divided into different categories; sand casting, investment casting and permanent mould casting. Factors that influence the choice of casting method are quality, cost and environmental effects. (Srinivasan, 2012)

In sand casting the mould material is made from tightly packed sand. The advantages of sand casting are design flexibility, low cost and possibility for a wider selection of alloys. The two-piece mould is commonly filled with coarser sand as filler and finer sand around the pattern for a better surface finish. The feeding system consisting of a pouring basin, sprue and runners connected to the mould cavity. It can be a part of the pattern or carved into the mould. Sand casting allows for casting of simple and complex parts and has been used in the automobile industry when casting crankcases and cylinder heads. A new mould is required after each casting cycle, which is disadvantageous but manageable with smaller production quantities. (Beddoes & Bibby, 1999)

Investment casting or lost wax casting is a more tedious process where a pattern of the part is first made from wax. The wax pattern is the covered or coated with refractory material and binding agent to create a shell. By heating up the shell and melting the wax the two can be separated. Molten metal is then poured into the shell and after the metal solidifies the shell is broken to reveal the final piece. The advantages of investment casting are high accuracy, precise dimensions, high quality and detail as well as the ability to create complex geometries with thin walls. (Beddoes & Bibby, 1999)

Permanent mould casting is as the name suggests a casting method where the mould is reused many times. This casting process is more suitable for large-scale production. Simplified, the process involves pouring material into a mould and extracting the cast without damaging the mould itself. Such mould design can be complicated and therefore significantly more expensive. When metal casting the mould material has to have a higher melting temperature than the casting material. Permanent mould casting can be further divided into gravity die casting, low pressure die casting and high pressure die casting. (Beddoes & Bibby, 1999) Gravity die casting means the materials travel through the runners and cavities with the help of gravity. Meanwhile, low pressure die casting uses external pneumatic pressure of around 0.5-1 BAR to feed the material through the feeding system. High pressure die casting utilizes a higher pneumatic or hydraulic pressure than low pressure casting and is more suitable for complex shapes. Solidification and cooling times can also be shortened with high pressure casting, allowing for higher productivity. (Waters, 1996)

2.4 High pressure casting of sanitary porcelain

2.4.1 Moulding

Cambridge dictionary define a mould as follows,

> ” A hollow container with a particular shape into which soft or liquid substances are poured, so that when the substance becomes hard it takes the shape of the container.”

A mould can also be referred to as a die, cast or form. (Cambridge Dictionary, 2021)

When designing a mould, it is of importance that the part itself is designed in a way that suits casting. A more complex part requires more time designing the mould but can also delay casting cycles. Surface finish, number of cavities and casting technique all have to be considered when making a mould. Furthermore, the removal of the part from the mould need be considered, angling the walls of the mould can allow for easier ejection (Riley, 2012)

2.4.1.1 Mould design and mould material

When designing a mould for casting, especially ceramics one must consider the shrinkage that occur. Shrinkage in ceramic casting occurs during the drying phase and during the firing stage. The total shrinkage is about 12-14%, however the shrinkage is not equal across the piece. Geberit's Renova 36 washbasin as an example is compensated with 12-12,3% in x and y-axis while the height or z-axis is 14,5%, seen in figure 3. The surface area XY is against the drying cart when drying. The top of the washbasin at the z-axis lacks external support and tends to lean either forwards or backwards, this is also considered when compensating in the design. (D. Brandt, personal communication, 2021)

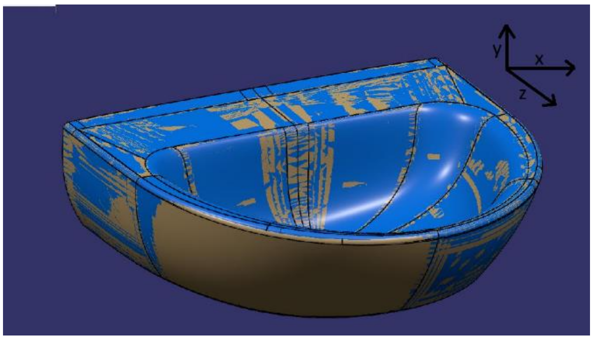

Figure 3: XYZ-axis in relation to WB

After the washbasin itself has been designed and the compensation for shrinkage has been applied, the two mould pieces can be designed. In figure 4 one can see the complete package with two mould parts, plates and supports, as well as the female part of a mould. In the bottom left corner is the feed-point for ceramic slip and casting pressure.

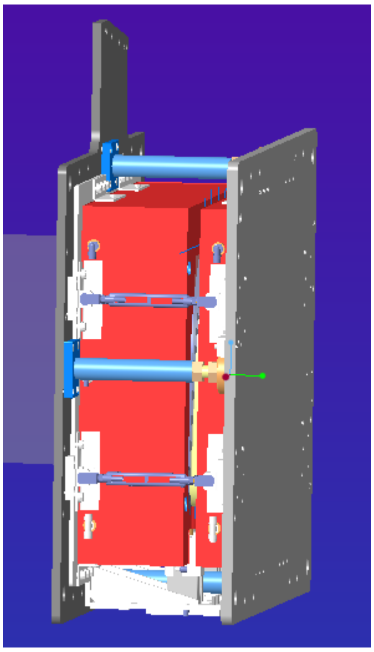
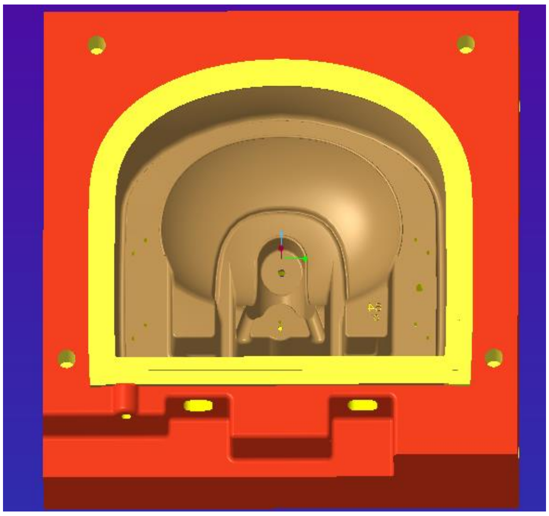

Figure 4: Mould package and female mould part

The moulds used at Geberit’s factory in Ekenäs are made out of a polymer-blend that can withstand a slip of up to 50 degrees celsius. The materials is porous and allows for water to be absorbed. When designing the moulds, capillarities seen in figure 5 are drilled from the outer parts of the mould. These are connected to a network of runners with eachother on the backside of the mould. The capillarities are drilled to a 3cm distance from the mould surface and allows for an easier exit for water from the porous mould material. Further more the capillarity is supplied with air, vacuum and water that can be applied when de-moulding, cleaning and drying the mould. (D. Brandt, personal communication, 2021)

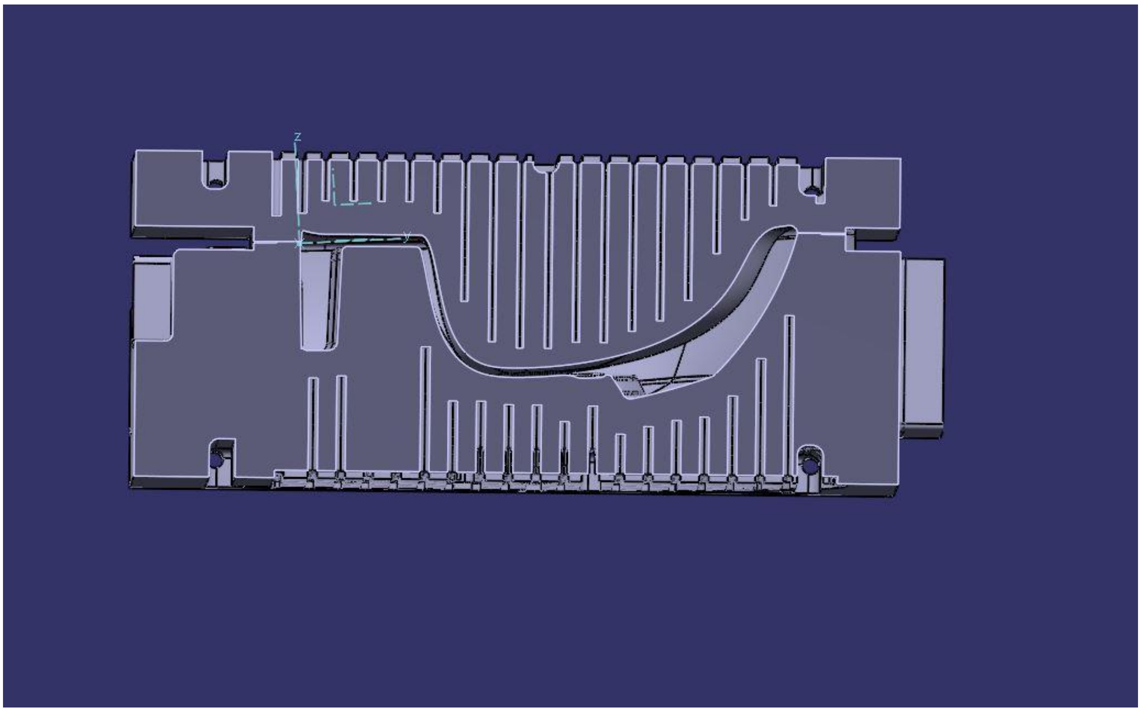

Figure 5: Side profile of mould in Catia

By design the sealing surface between the moulds is at a slight angle as seen on the right of figure 6, the sealing surface is also designed to align the moulds correctly with the help of the guidepins.

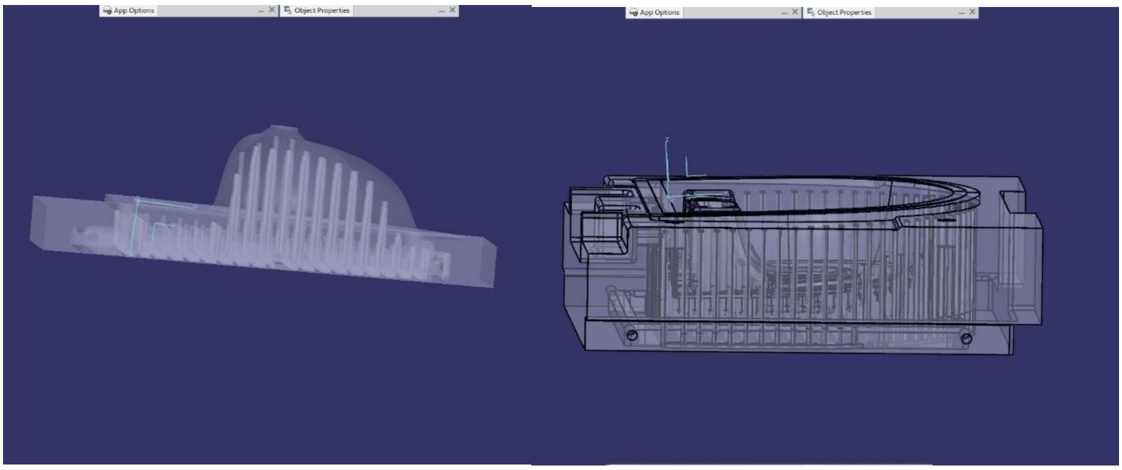

Figure 6:Male and female of two-part mould in Catia

2.4.1.2 Installation of mould into casting-battery

The moulds are installed into the PCL casting machine at an angle of 10 degrees, back-to-back. The mould plates are bolted together, the back of one female part to another moulds male part and they slide on a traverse when opening and closing. Position of the mould in the battery will be investigated further as it can be possible that pressure within the moulds or waiting for de-moulding can affect moisture level and quality of the piece.

2.4.2 Casting

High pressure casting is a manufacturing method that removes water from the ceramic slip by pressing it through the walls of the mould. This is achieved by applying a casting pressure to the slip feed, in high pressure casting it is usually above 10 bar. Water can then escape through the capillarity in the mould material. This allows for the slip to stick to the wall and form thickness. The high-pressure casting of washbasins at Geberit in Ekenäs is done with a casting machine made by PCL ceramics seen in figure 7. (Geberit Production)

Figure 7: PCL Ceramics PC570 casting machine (Source: PCL570 manual)

According to SACMI the pros of high-pressure casting is:

- Amount of casting cycles per day
- Reduced personnel requirements
- Space requirement per piece

- Less finishing work on cast pieces
- Improved uniformity and quality

The one con is the high investment cost of high-pressure casting. (SACMI, 2010)

The PCL-machine can hold 10 moulds in its' battery and produce 1-2 washbasin per mould per cycle, depending on model and size of washbasin. Casting is done in cycles that are programmed; each cycle takes around 15 minutes and follows the order seen in figure 8.

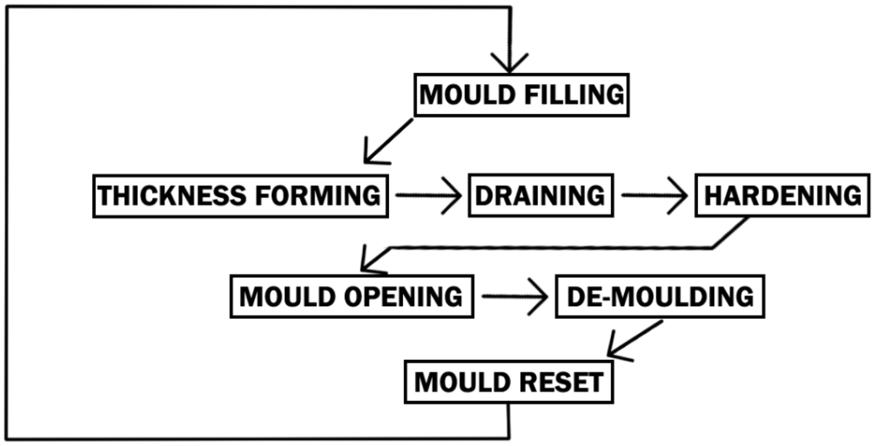

Figure 8: Casting cycle

Each mould is fed water and air through hoses to its' capillarity as explained in the mould chapter, ceramic slip and air is fed through the feeding hole and excessive slip is emptied through the feeding hole. In figure 9 below one can see the two 1/2-inch feed line to a mould that produce two pieces per cycle and the 3/4-inch feedline to a mould that produce one piece per cycle. At the bottom of the picture valves that close during hardening can be seen, along with white pressure lines, the thicker yellow and turquoise lines provide the capillarity with water and the thinner blue line supplies air. (Geberit Production)

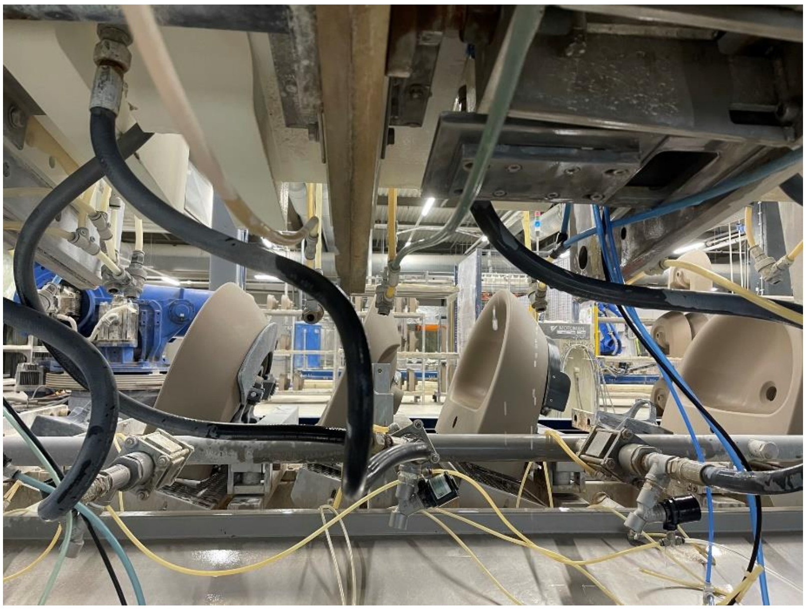

Figure 9: External mould piping

Even though each mould has its own slip feeding point into the mould the pipes are all connected and fed with a diaphragm pump, some functions can be individually controlled for each mould. Enough slip for two casting cycles is stored in the casting machine's own tank, the diaphragm pumps the slip through the pipeline into each mould until they are filled to a certain pressure. Pressure is measured in a pressure vessel in the beginning of the pipeline, as the moulds fill up the pressure inside the pressure vessel rises and is indicated on the proportional valve (referred to as propo). 2,7 bar at the propo indicates the moulds are filled and then 10-11 bar of air pressure is applied through the top of the vessel. This pressure is called casting pressure and allows for thickness to form on the walls of the mould as water is extracted through the porous mould surface and capillarity. Excessive slip is drained from the mould when desired casting thickness is achieved. Emptying pressure is fed through a hole opposite of the feed to allow for slip to escape through the feed/drain hose. Alternatively, air pressure can be fed through the sink hole at the bottom of the washbasin. The slip is pumped to a return tank by another sandpiper and the return slip is fed to the main slip storage, ready for use in other casting cycles. Post-emptying the cycle goes into hardening. Hardening means the valve from the sandpiper pump closes as well as each individual valve into the moulds. The hardening pressure is applied between 1.8-3 bar into the mould and can be individually controlled by pressure valves, hardening continues at constant pressure for a set period. SACMI states that it is necessary to ensure solid-cast parts of the piece are already hardened during thickness forming and that hollow-cast parts are properly drained of water before hardening to reduce the hardening time. When hardening is done the pressure within the moulds are released and the mould opening phase begins. The mould opening phase means the pressure on the battery releases and one mould at a time opens. De-moulding is done by a robot and each mould has its individual de-moulding support that the robot can lift using its' tools, see figure 10. As the mould opens the moving side of the mould is supplied with water and air through the capillarity to release from the piece avoid sticking. (R. Kallström & J.Pihlström, personal conversation, 2021)

Figure 10: De-moulding support

When the support is in position as seen in figure 11, water and release pressure is applied to the remaining side of the mould. Flushing water through the pores and blowing air releases the piece from the mould surface and the piece is held in the de-moulding support.

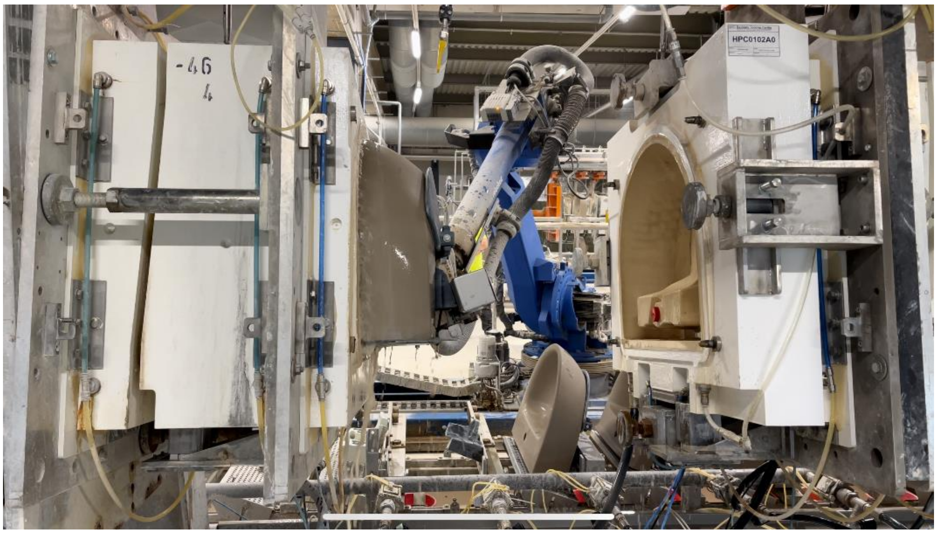

Figure 11: De-moulding process - closed mould on the left, open mould in the middle

The robot then places the piece along with it support down in the rack behind the machine (figure 12), ready to start drilling the overfilling hole while the machine resets for the following cycle. After de-moulding the mould is reset by feeding water through the capillarity and automatically rinsing the mould surfaces, followed by vacuum to dry the mould surface before finally closing the mould again. The machine is now reset and pressure on the battery can be applied again, however due to the time it takes for the robot to finish drilling all de-moulded pieces a delay has been set to avoid casted pieces waiting in the machine before de-moulding. (J. Pihlström, personal conversation, 2021)

Figure 12: PCL machine, de-moulding rack and robot

2.4.3 Maintenance

At regular intervals, usually weekly basis, maintenance is done to the casting machines. The moulds are treated with chlorine or glydol, the cleaning substance is sucked into the mould using vacuum and then cleared out using water and air. Cleaning the mould in this manner maintains the porosity and absorbency. If, however the mould surface is blocked and absorbency is lost it can be sanded until absorbency is restored. Furthermore, the weekly maintenance allows for all the tubing and piping to be checked, excess slip to be cleaned out of the gutter under the battery and the tools that the robot use to be maintained. (R. Kallström, personal conversation, 2021)

2.4.4 Drying

Drying is defined as the process where moisture is removed from a material, most commonly conceived as removing water with hot air. It can, however, include any type of liquid turned into heated gas. Drying takes place when the material obtains heat from the surrounding, through convection, conduction or radiation, water in the body then evaporates and escapes from the surface. (Keey, 2011)

During the drying stage of the production water that is not chemically bound to particles within the piece is removed. This includes water between the gaps of the particles and surface water surrounding the particles. Drying starts as soon as the piece is removed from the mould and can take from 6 to 18 hours. In ceramic casting water evaporation has shown to be affected by air flow, surface area of the piece and humidity in the piece as well as surrounding drying air. (SACMI, 2010)

There are two stages when drying a piece, the green stage and white stage. The green stage and green drying is also referred to as leather-hard drying. This is the preliminary drying that occurs when the piece is removed from the mould. Green drying makes the piece stronger and easier to work with. Most of the drying shrinkage happens during the green stage. White stage and white drying is when the last moisture content of the piece has been removed from the piece, leaving a moisture content of around 1%, usually done with forced draught drying. (SACMI, 2010)

The workability of the piece is at its' maximum during the green stage which allows for finishing touches such as removing marks or sharp corners using a sponge, this can be done with automated robots or by hand. It is important to avoid deformation during this operation. White finishing is done on a piece close to zero percent humidity and the workability of the piece is restricted, however the risk of deformation is minimal. The operations in white finishing are like that of green stage. (SACMI, 2010)

At Geberit in Ekenäs most of the green stage drying happens in still air while the pieces are waiting for the drying cart to fill up. The drying is then finished in a drying tunnel (figure 13) that produces force-draught with control over circulation, temperature, and humidity. After the drying cycle in the tunnel the pieces are left with 1-2% moisture. The newer production line will have pre-driers which provide greater control over the green drying. According to SACMI this can optimize the drying cycle as the green drying would happen in the pre-drier and the tunnel can then be used directly at 110 °C improving holding time without risking further defects (SACMI, 2010).

Figure 13: Drying chamber and drying carts

2.4.4.1 Drying shrinkage

Drying shrinkage is the decrease in size that occurs when the material dries. As stated earlier most of the shrinkage happens during the green stage, more specifically it has been studied that noticeable drying shrinkage occurs until the moisture content of the piece is 13%, see figure 14. (SACMI, 2010)

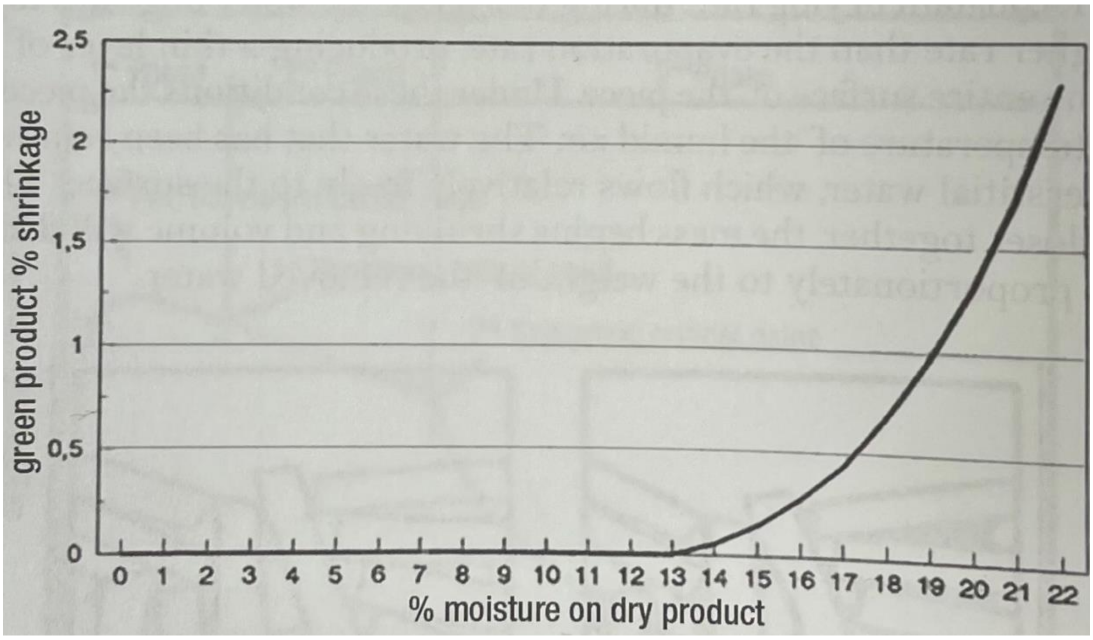

Figure 14: Drying shrinkage (Source: SACMI)

Yaciuk states that excessive drying shrinkage can be a result of an increase in drying rate, due to higher air temperatures or lower moisture. (Yaciuk, 1981)

Drying shrinkage in Ekenäs is measured in the lab, by casting a test piece of 100mm length and drying it to the same moisture level as cast products. The shrinkage is calculated using the following formula, where S_D is the drying shrinkage in percent, l_0 is the original length and l_1 is the length after drying.

Equation 2

$$S_D = \frac{l_0 - l_1}{l_0} \cdot 100\%$$

2.4.5 Glazing

Glazing is the process where the pieces is sprayed with a coating, this is performed after drying. The process can be done through manual or automated labour, automatic glazing is performed by a robotized process. (SACMI, 2010)

After drying, the tunnel is cleared, and the carts are placed into the glazing cells where robots finish the piece by sanding the surface on a sponge roller and then applying glaze by spraying. There are two cells for washbasins at Geberit in Ekenäs, depending on the type of washbasin they are guided to different cells. Glaze is applied to give the ceramic the sanitary coating that seals the pores and prevents absorption of moisture. It allows for easier cleaning and hinders bacterial growth.

2.4.6 Firing

Firing is the part of the production process where the ceramic product is subject to applied extreme heat. During this a change in volume, change in surface aesthetics and melting of mineral components in the ceramic occurs. The firing process causes crystal transformations with formation of new phases and a drop in permeability along with increased tensile strength of the product. (SACMI, 2010)

The firing at Geberit is done in kilns, TU2 and TU4(abbreviation from tunnel oven) are continuous flow tunnel kilns used for first fire. Refiring is done in an intermittent kiln and TU4. TU2 is one of the original kilns in the factory while TU4 is a more modern kiln (see figure 15). Both kilns are controlled by a firing curve and put through speed. TU4 have a mixed firing curve to handle first fire and re-fire products. (Geberit Production)

Figure 15: Riedhammer tunnel kiln (Source: Ceramic World Web)

Firing of sanitary ceramics is divided into three stages. Heating, holding at maximum temperature and cooling, this is controlled by the previously mentioned firing curve. Heating means the temperature is raised from ambient to around 1200 °C, the next stage then holds the temperature before cooling begins. The aggressiveness of the temperature increase, and length of hold is determined by company specifications and product requirements. (SACMI, 2010)

At 100 °C the absorbed water in the glaze evaporates and up to 150 °C residual water in the piece is removed. Heating here is gradual at a phase of 300 °C/h to avoid generated pressure from steam to damage the product. Between 150 °C and 800 °C a gradient of 350 °C/h can be used and during this stage combustion of organic substances occur. (SACMI, 2010)

From 800 °C to the maximum temperature (1200 °C) the gradient is reduced to 65 °C/h, the delay allows for the glaze to start melting. The temperature is then held at maximum temperature to allow for composition changes in body and glaze. The porosity of the product reduces to 0.5% because of sintering (explained in Slip parameters, Porosity) and the glaze melting into the pores.

Between 1200 °C and 800 °C the cooling gradient can be set at 800 °C/h, fast cooling at this stage gives the glaze the glossy surface. From 800 °C to 600 °C the gradient should be lowered to 150 °C/h and further lowered to 60 °C/h between 600 °C and 500°C to allow for quartz β to quartz α transition. Tensions can occur within the ceramic during this stage. Below 500 °C the cooling gradient can be raised as no further precautions has to be taken. (SACMI, 2010)

Jylhä-Vuorio also recommends that the temperature is slowly raised from 0 °C to 600 °C due to the quartz α to quartz β transition stage that occurs at 573 °C. Furthermore, it's stated that during cooling the reverse quartz transition takes place between 600 °C and 500 °C and it is recommended to slow down the cooling period during this as well as 300 °C to 200 °C. (Jylhä-Vuorio, 2003, s. 55)

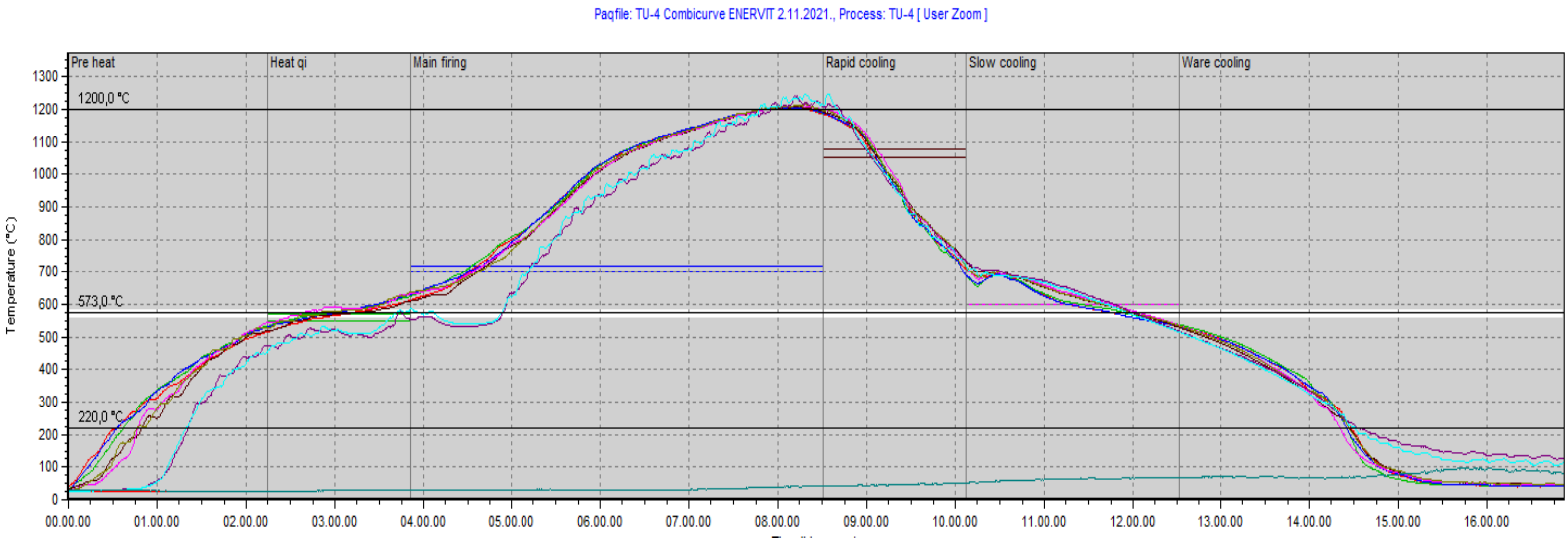

Figure 16: Firing temperature curve TU4

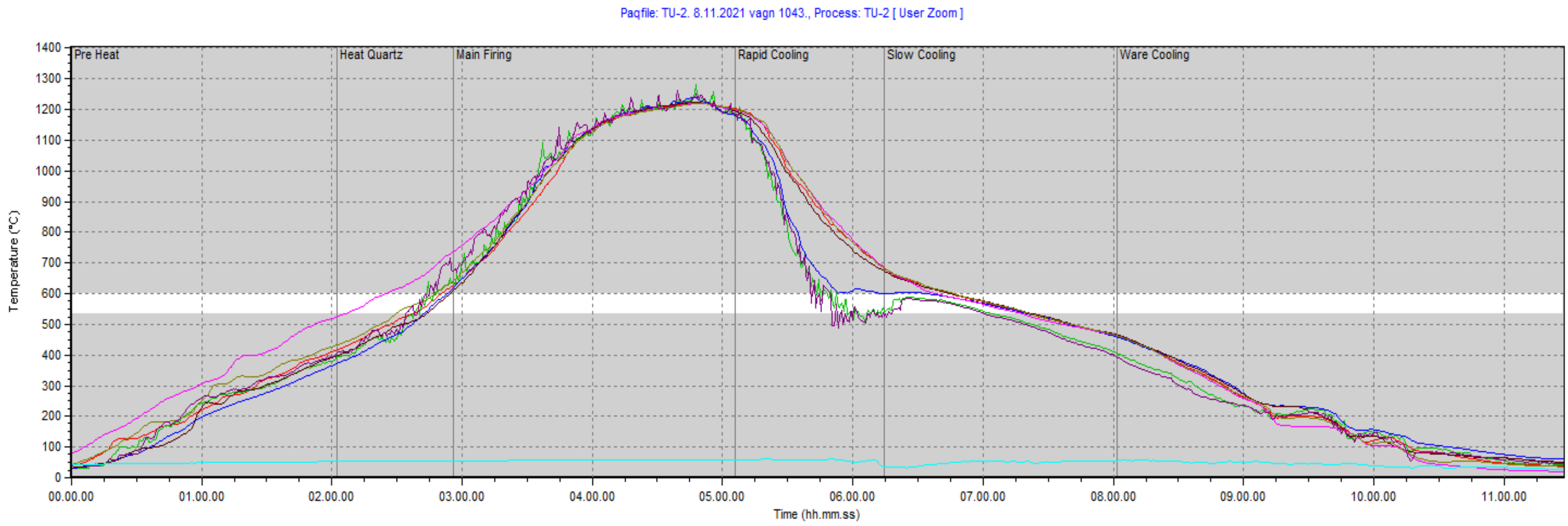

Figure 17: Firing temperature curve TU2

In figure 16 and 17 one can see firing temperature curves from TU4 respectively TU2, temperatures displayed on the y-axis and time in hours on the x-axis. The main difference is the steepness seen on the heating phase of TU2 compared to TU4. This is due to TU4 being used for first fire in combination with re-fire. After 600 °C the temperature of TU2 is rapidly raised to 1000 °C before it is slowly allowed to reach its maximum of 1200 °C. On the other hand, TU4 is held at 573 °C for an extended period of time, the quartz transition is more gentle and requires more time as some pieces have been fired once before, both Jylhä-Vuorio and SACMI engineers recommend this slow gradient. The cooling curve is similar for both kilns with the slower gradients as recommended previously by Jylhä-Vuorio.

2.4.6.1 Firing shrinkage

The shrinkage that occurs during firing in the kiln is due to the vaporization of water bound to the particles within the product. Around 3% of the firing shrinkage is due to sintering. The quartz α to quartz β transition counteracts the shrinkage during heating as this increase the volume 2-3%, however, density drops, and the transformation can be regarded a weight loss. (SACMI, 2010)

Firing shrinkage in Ekenäs is measured by firing the same test tile as for drying shrinkage and using the following formula where S_F is firing shrinkage in percent, l_1 is the length after drying and l_2 is the length after firing.

Equation 3

$$S_F = \frac{l_1 - l_2}{l_0} \cdot 100\%$$

Therefore, the total shrinkage S_T of the product is

Equation 4

$$S_T = \frac{l_0 - l_2}{l_0} \cdot 100\%$$

Total shrinkage in October 2021 was measured between 11,6% and 11,79% on different test tiles. The total shrinkage consisted of roughly 2,8% drying shrinkage and 9% firing shrinkage. (Geberit Production)

2.4.7 Final check (Sorting, quality control)

Sorting or quality control is a part of the manufacturing process where the finished piece is inspected. The controller will class the product in three different categories, no defects, limited and repairable defects and rejected. No defect or fired good are products within all tolerances and guidelines that can be sold. Limited and repairable defects are products with minor faults that can be repaired by the controller and then refired. (SACMI, 2010) Rejected or fire scrap is products deemed unrepairable or bad repair of refired goods, these are scrapped and disposed of by an external company that recycle ceramic scrap into bricks.

The inspection process varies depending on product but for washbasins it is similar across the board. First a visual inspection is carried out, the controller inspects for visible cracks, dark spots or deformation. The controller then uses a rubber hammer to hit the product, this produces a different tone if any hidden cracks appear and lastly the product is checked for dimensional deviation on a stone table. Depending on the type of washbasin different tolerance tools are used, 4mm for WB35 and 5mm for WB36. If everything is within tolerances the product is packed and reported good. Necessary repairs are conducted if the product is to be refired and the product is reported as scrap if it is beyond repair. Cracks and dimensional deviation that will be further discussed in the defects chapter are faults beyond repair. Meanwhile iron spots, bad finishing or faults in less visible spots can be repaired (SACMI, 2010).

2.5 Defects

2.5.1 Casting defects

Casting defects can occur throughout the casting stage; from filling the mould, fluid slip solidifying, hardening to de-moulding. The automated nature of the high-pressure casting method is problematic regarding the correction of casting defects as compared to low-pressure casting where most problems can be repaired afterwards. (SACMI, 2010)

2.5.1.1 Cracks in or along hollow-cast and solid-cast parts

In high-pressure casting cracks can emerge in and along the interface of the hollow-cast and solid-cast parts of the piece, these cracks have a jagged appearance as seen in figure 18. Such cracks can be caused by insufficient hygroscopic content of the mould, excessive hardening time, excessive thickness forming time or deformation. Insufficient hygroscopic content indicates the mould cannot absorb enough water from the cast through the capillary. This can be solved by adjusting the hygroscopic content at the beginning of the casting cycle. Deformation during this part of the casting cycle is often caused by softening of the cast due to the lack of hardening, which in turn lead to internal stress. Excessive hardening can lead to cracking as well. Incorrect hardening times as well as thickness forming times can be solved by adjusting and optimizing said values in the casting machine until satisfactory results.

Insufficient pressures and mould opening times can induce open cracks on the weakest parts of the ceramic cast without deformation in the surrounding parts of the crack. Meanwhile excessive pressure and mould opening times lead to closed cracks along with surrounding deformation. Cracks in the hollow- and solid-cast parts can also be consequence of problematic mould conditions, for example reduced thickness forming in certain areas due to lower functionality regions of the mould. Stagnation of water within the mould create a drop in density of the slip which in turn lead to discontinuities in the ceramic slip. Cracks caused by stagnating water do not appear continuously as it requires the build-up of water in the mould. The solution to this is to make sure water is expelled from the mould as intended, during the cycle-stages. (SACMI, 2010)

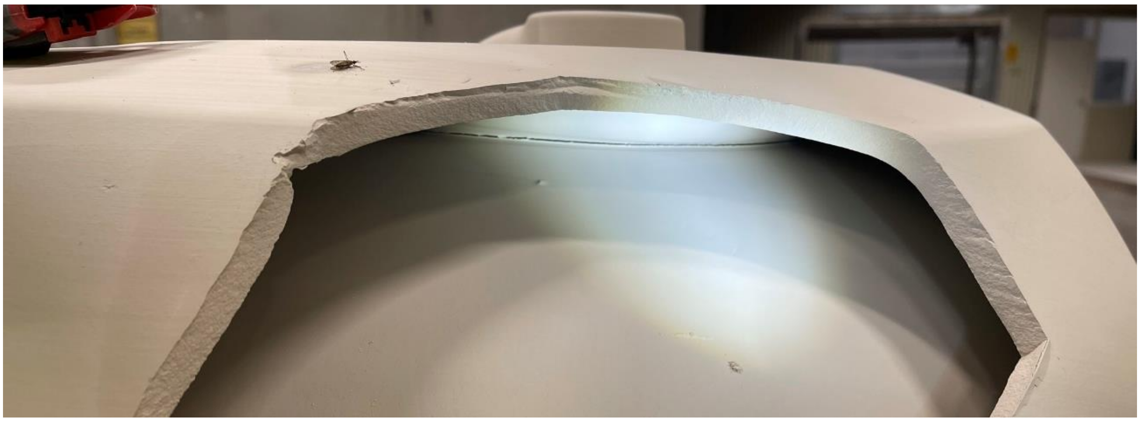

Figure 18: Crack along the hollow and solid cast edge, jagged

2.5.1.2 Cavities, gaps and separation of formed thickness

Small holes or cavities of no larger than 4-5mm within the ceramic body or close to the surface can have multiple causes. The occurrence of foreign fluids or bodies in the slip is the main cause, an example of this is water residue left in the tubing. A defective slip feed or inadequately sealed pipes can draw in air and as a result air bubbles form within the cast. Such defects are elevated in high-pressure casting as the casting conditions and pressures are more intense. Liquid residue can emerge from the water treatment stage in between casts if mould surface or delivery tubing is not sufficiently cleared of liquid before starting a new cycle. The lack of continuous slip feed within the mould usually caused by modelling errors can result in cavities of varying sizes filled with liquid slip or gaps separating the cast formed on opposite mould parts. To solve the issue in high-pressure casting extended thickness forming time can be applied. Gaps filled with water is a sign of failure to evacuate the water in the early stages of filling, hence investigating if water is properly released before the casting cycle begins is the first step, followed by ensuring proper casting cycle setup. (SACMI, 2010)

2.5.1.3 Ripples (Valkki)

Ripples are linear introflexion or inward bends, usually found on the hollow-cast parts of the cast. This defect becomes easily visible after firing, however they form during either mould filling or draining. Increasing the filling rate and pressure can shift the position of the ripple but not completely remove it, generally the ripple is more noticeable at lower filling rates and pressures. Contrarily if the defect is caused during draining the source is excessively high evacuation or draining pressure and speed. Reducing filling or draining pressures and modifying slip formula can eliminate the defect. If the ripple persists, mould modifications must be made – more specifically, increasing the number of slip or air feed points to reduce the impact of the ripple. (SACMI, 2010)
At Geberit's factory in Ekenäs ripples are referred to as bumpy surface in English and in common mouth "valk or "valkki".

2.5.1.4 Casting deformation

De-moulding may cause slight deformation or tendency for the piece to collapse due to the quite soft state of the ceramic body in the de-moulding stage. The cast piece may not be homogenous across its formed thickness leading to firmer external parts and possibly increased moisture levels in internal parts of the cast. Above mentioned differences create tensions within the cast that are released in the form of unrepairable cracks within the hollow-cast parts. Incorrect hardening times or timing of emptying the mould can lead to deformation or extensive softening of the piece (figure 19). The hardening of the cast can be obstructed by an increased amount of water in the mould porosity leading to moist walls and instability of the cast. De-moulding in a multi-mould machine can also lead to water contained in the mould to be transferred back into the piece through the capillarity, due to a delay in the de-moulding. (SACMI, 2010)

Figure 19: Soft piece

The impact of positioning a mould later in the casting-battery and thus causing longer delay before it gets de-moulded will be investigated.

The cast may also be subject to deformation while draining the excessive slip from the mould, thus removing the support for the outer walls. Air is used to exert pressure against the walls before draining and prevent collapse. After draining the excessive slip, compressed air is added in the hollow-parts causing hardening, the pressure is then released before opening the mould to avoid deformation in the opposite direction. (SACMI, 2010)

The impact of increasing hardening pressure or hardening time will be investigated. The possibilities to combine a later position in the battery with increased hardening will also be investigated as it would be beneficial if running multiple moulds of larger sized pieces in the same casting-battery.

The cast can be subject to deformation by gravity when the support provided by the mould itself is removed during the de-moulding process. Additionally, de-moulding in high-pressure casting is done by applying air and water pressure to detach the cast from the mould, which also can lead to deformation. The higher the air/water pressure when de-moulding the more likely it is to cause warping or deformation; however too low air/water pressure can lead to imperfect removal from the mould. Thus, also causing deformation or warping. A higher moisture level in the cast is more likely to lead to deformation when the mould is opened. Mould opening can cause dragging that lead to deformation. (SACMI, 2010)

Analysis and investigation on the impact of de-moulding pressures and mould opening behaviors along with robot movements will be conducted later in the thesis.

Despite taking all precautions a ceramic cast can have tendency to deform, this can be fixed through structural modifications to the piece thus making the piece stronger. The addition of support ribs, use of hollow-casts or increased thickness in solid-cast are examples of such modifications. (SACMI, 2010)

2.5.2 Drying defects

Cracks is the most common defect that occur during drying. Ambient conditions of the surroundings like humidity and temperature critically affect drying. Insufficient relative humidity (Rh) causes faster evaporation of water from the cast during still air drying. Excessively fast evacuation rate of moisture from the piece result in internal stresses due to the cast shrinking. Tensions within the piece caused by casting are accentuated during the drying stage. The cracks appear as a result of greater stresses during the drying stage. These stresses are further accentuated when comparing forced draught to still air drying, due to applied ventilation and higher temperature. With correct drying cycles the pre-firing shrinkage should be over before forced draught drying. Most of the pre-firing shrinkage happens during still air drying and the cast’s moisture content is between 18% and 13%. It is worth noting that supports or surfaces that limit shrinkage induce further stresses and deformation. Such deformation and the unrepairable fragile nature of a dried ceramic can generate cracks during firing. If ambient conditions are not met it is recommended to limit air circulation or cover the materials with plastic or waterproof sheeting. Therefore, slowing down the evaporation and making the process more gentle. (SACMI, 2010)

In the Ekenäs factory the first stage of drying happens when the piece rests in the demoulding support while the robot roll the seam and drill the hole to the overflow channel. However, the majority of the still air drying occurs after the robot has carefully placed the washbasins on a 3-floor cart (figure 20). To minimize friction and allow for shrinkage, each floor is layered with a loose sheet that can also be covered in talc.

Figure 20: Drying cart and washbasins

2.5.3 Transportation defects

The manual transportation that takes place when moving the cart from the casting cell into the drying tunnel and then glazing cell, must be executed carefully. The extensive handling subjects the pieces to more stress. Importantly, the floor must be in excellent condition. Joints or cracks in the floor can jerk the pieces and indirectly damage the very fragile green piece. Automated transport mechanism minimizes the risk of rejection due to transport damage (figure 21) as the piece is subject to less jolts and jerks. Automatization also allows for easier identification where damage can occur as it removes the variable of different operators transporting the carts. (SACMI, 2010)

In Ekenäs glazing and loading of kiln carts thereafter is handled by robots. Automated guided vehicles (AGVs) transport the kiln carts to the kiln for firing. However, the AGVs also drive over the floor, meaning the importance of smooth flooring persists also outside of the foundry and glazing area.

Figure 21: Transport damage

2.5.4 Glazing defects

Glazing defects can often be recognized immediately and repaired to avoid compromising of quality. Defects with the glaze can occur if the glaze itself is faulty or the application is done improperly. Manual glazing allows for defects to be noticed immediately. However, manual glazing defects are usually caused by the worker and are therefore non-repetitive and subjective. Without repetitiveness defects are hard to solve definitively. Glazing done by a robot allows for repetitiveness and definitive solution when problems have been identified. However, robot glazing requires quality control checks as the robot itself cannot detect defects. (Geberit Production) (SACMI, 2010)

2.5.4.1 Imperfect glaze surface

An imperfect glaze surface is usually a result of improper application, it can occur if the second layer of glaze is applied too quickly, not letting the first one dry completely. Furthermore, the glaze layer can be deformed if too much compressed air is used during application. If the glaze surface has imperfections as a result of the glaze, the reason can be too dense glaze or low amount of binder. (SACMI, 2010)

2.5.4.2 Small cracks in the glaze layer

Small cracks and breaks in the glaze layer can be caused by excessive application of glaze, insufficient amount of binder in the glaze or too fine particle size.

2.5.4.3 Exfoliation

Low amount of binder in the glaze or contaminated surface of the ceramic body can lead to improper adhesion. This leads to exfoliation, the glaze layer comes loose from the ceramic body, leading to discontinuity in the surface. (SACMI, 2010)

2.5.5 Firing defects

Firing can reveal or worsen defects already present in the cast from previous stages. New defects can also occur during the heating and cooling process, due to the mineralogical transformation that the piece is subject to. Defects during firing can be categorized into body defects and glaze defects. Body defects consists of cracks (figure 22), deformation and surface irregularities, while glaze defects include staining, glaze shrinkage, crazing and other bad finishing. (SACMI, 2010)

Figure 22: Crack after firing

2.5.5.1 Cracks and cooling cracks

Cracks that stem from earlier production stages can be distinguished from cooling induced cracks by analyzing the edges. Round edges and a more ragged appearance indicate an already existing defect or defect induced by the heating phase. Such cracks can be caused by accumulated tensions or deformations from the earlier production stages. Conchoidal cracks with sharp and well-defined edges indicate the defect emerged during the firing process. Furthermore, cooling cracks can be distinguished by the conchoidal cracks with portions of sharp-edged glaze (figure 23). Achieving an optimal cooling-gradient is important to avoid cracks forming during the transformation between quartz α and quartz β. During the quartz transformation the piece is subject to tension due to volume changes. Moreover, differences in temperature due to how the kiln cart is loaded or temperature zones in the oven can result in tensions followed by cracking. (SACMI, 2010)

Figure 23: Cooling crack

2.5.5.2 Deformation

The piece is subject to deformation during firing as the state changes from fragile to viscous-plastic and back to fragile. Shrinkage is further accentuated during firing and as such the process can lead to intense deformation and formation of cracks. Contact surfaces that do not allow for shrinkage can generate tensions within different parts of the piece, resulting in warping. By focusing on weak parts during the modelling of the piece one can try to minimize the problem, another solution could be the addition of support-ribs. (SACMI, 2010)

2.5.5.3 Surface irregularities, coloring and bubbles

Small defects that compromise the uniformity of the glaze layer can be classed as surface irregularities. These defects can occur from contaminates, air bubbles or water droplets in the body. Contaminates can lead to discoloring of different color, depending on the contaminate in question. Separation of solid-cast parts can occur if air bubbles are present. Such defects can be apparent on the surface of the piece even though the bubble is formed in the body. Bubbles are further accentuated if the piece is re-fired as the trapped gases are unable to escape through the sealed glaze on the surface. Applying a gradual firing gradient can allow for better gas release. Moreover, a suitable glaze composition that delays the softening point can allow for trapped gases to escape. (SACMI, 2010)

2.5.5.4 Staining and pin holing

Stains and spots of different sizes appear when the piece is subject to metal contamination. The glaze is normally cleared from contaminates through sieving and de-ironing. Contamination can occur from prolonged storage where the piece is exposed to metal dust. During firing the piece can be exposed to oxide dust, contaminates from the chimney. Surface imperfection such as the glaze layer boiling can occur if the raw materials have been contaminated.

Small cavities ranging in size from a few micrometers(μm) to a few millimeters(mm) are referred to as pinholes. Pinholes appear on the surface of the glaze and are caused by gas exiting the body through the glaze. Comparing the pin holing defect to earlier mentioned bubbles, the pinholes are smaller and only occur in the glaze layer. (SACMI, 2010)

2.5.5.5 Glaze shrinkage and no glaze on edges

When glaze shrinkage occurs, it leaves a part of the body exposed, the surrounding glaze edge remains round as seen in figure 24. The bare part appears like it was never glazed. Such defects can arise from dirt on the ceramic piece leading to improper adhesion of the glaze layer. Shrinkage can also occur when too much glaze is applied, this would in turn lead to unfired glaze with small cracks. Particle size within the glaze affect the internal cohesion of the glaze, thus too small particles lead to surface tension. This can be spotted before firing as discontinuities in the glaze layer. Lastly shrinkage can occur if there is an insufficient amount of binder in the glaze, allowing for excessive shrinkage. Furthermore, lack of binder in the glaze can lead to glaze missing on the edges of the piece. This can also be the case if the melting point of the glaze is too high or if there are considerable differences in the shrinkage coefficients of glaze and body. (SACMI, 2010)

Figure 24: Glaze shrinkage

2.5.5.6 Crazing

Crazing are small cracks in the glaze, similar to cooling cracks but only compromising the glaze layer. They can be identified as dark lines that interrupt the uniformity of the glaze layer. The defect occurs due to tensions and can appear as the piece exits the kiln or be delayed by months after firing. As such the defect can be impossible to detect and lead to complaints from customers, therefore costing the producer. Crazing allows for moisture to enter the body through the glaze. The absorption of moisture then highlights the crack from its' surroundings. To avoid crazing the glaze's expansion coefficient must optimized. A lower expansion coefficient than the ceramic's expansion coefficient leads to compression instead of tension. This is the wanted outcome as glass resists compression better than tensile forces. (SACMI, 2010)

2.6 Pressure drop and resistance of flow in pipes

Pressure drop in piping systems is defined as the difference in pressure between two points of the piping network. Potential pressure drops need to be considered when determining size and power of pumps and motors in the piping system. (Process Equipment, Sanitary Processing, 2020)

The pressure drop is affected by both fluid properties and mechanical components. Fluid properties that affect the drop in pressure are density, heat capacity, temperature, and viscosity. Shear within the pipeline can cause changes in viscosity due to friction if the fluid is thixotropic. Length of the pipe, number of bends and complexity of the piping systems are mechanical components that affect pressure drop. Furthermore, the cross-section of the pipe and the internal surface roughness also affect pressure drop. (Process Equipment, Sanitary Processing, 2020)

2.6.1 Pressure drop

A formula to calculate pressure drop in multiple cavity moulds(seen in figure 25) is given as below:

Equation 5

$$\Delta P = \frac{8 \cdot \eta \cdot L \cdot Q}{\pi \cdot R^4}$$

$P = pressure$

$\eta = viscosity$

$L = length\ of\ the\ channel$

$Q = volume\ flow\ rate$

$R = radius\ of\ the\ channel$

(Crawford & Martin, 2020)

The formula is similar to Poiseiulle’s equation that is used when calculating pressure loss in rigid piping. (Flow in Tubes, 2022)

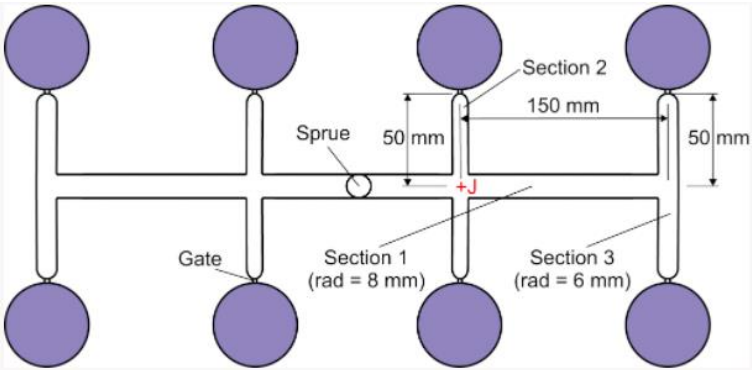

Figure 25: Multiple cavity mould (Source: Plastics Engineering p.55)

The idea of a pressure loss or decrease between the moulds existing in the battery cannot be verified through measuring as the casting-battery lack such probes. However, the idea is to apply the above theory of multiple mould cavities on the battery of 10 moulds to quantify if such loss exists. In the chapter for mould placement within the battery, practical test results regarding different pressures according to mould position can be seen.

3 METHOD

3.1 Measurements

To gain further information about shrinkage and possible differences between the products from different moulds during the stages of production a 3D-scan and measurements were planned. The focus was to determine if dimensional deviation can be tracked to the later stages of production or if it arises during casting.

3.1.1 3D-scan

Two pieces from different moulds of the productline Renova was 3D-scanned, using Creaforms Handyscan. Mould 5(M5) for WB36 as it was the oldest revision in production and had the most stable results regarding dimensional deviation. Mould 9(M9) for WB36 was scanned as it was the newest revision in production and with added compensation compared to M5. Reflective stickers attached to pins were placed over the piece to allow for the scanner to determine distance to surfaces, seen in figure 26.

Figure 26: WB36 with reflective pins

The washbasins were placed on different drying carts by programming the robot and handling while green was kept to minimum. The pieces were scanned approximately 10 minutes apart, immediately after being removed from the de-moulding support. Figure 27 shows Creaform's application producing the digital picture.

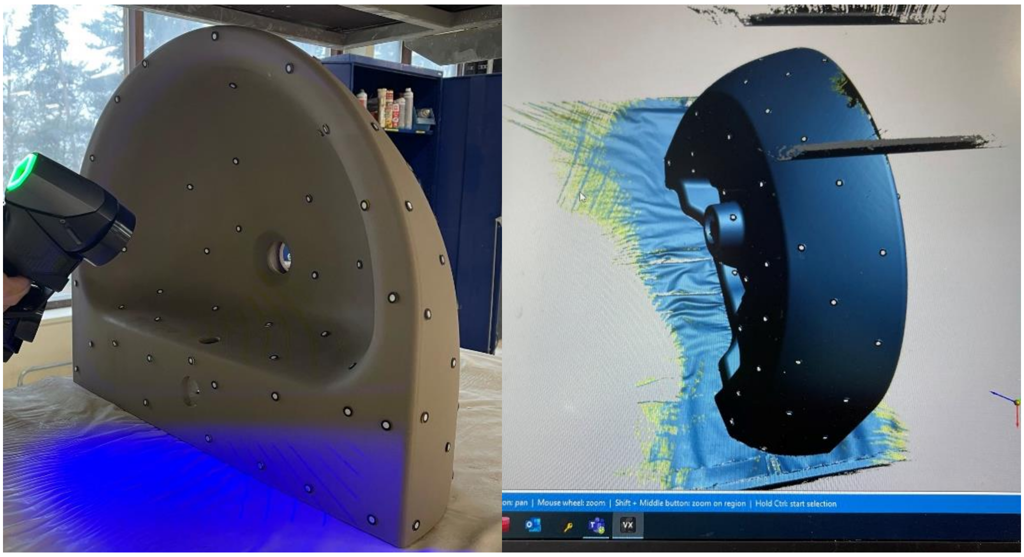

Figure 27: Scanning process

When drying the pins had been pushed out of the pieces as it shrunk and therefore, they had to be removed, leaving slight marks on the surface (figure 28). New reflective stickers were added on the same locations before scanning again and the program was set to smooth out surfaces where possible. The washbasins were then fired, and a third scan was taken.

Figure 28: Dry piece before scanning

3.1.2 Measurements

Five measurements (specified in figure 29) were taken on the same pieces used for the above experiment. Each measurement was taken using the same metal ruler and Vernier caliper, results were logged into Microsoft Excel. Measurements were taken immediately after 3D-scanning for both the green and white stage as well as after firing.

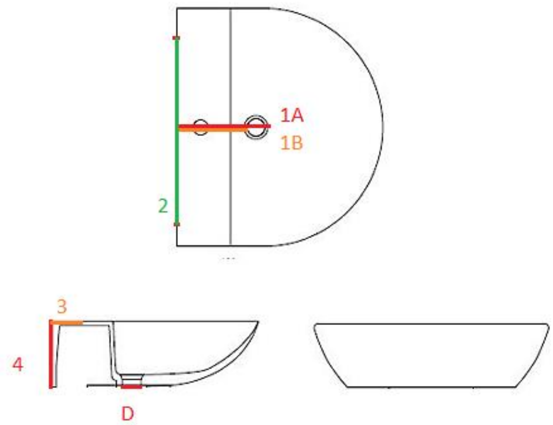

Figure 29: Measurements

3.1.3 Dimensional deviation tool

To make it easier to identify the significance of dimensional deviation a tool was designed. The purpose of a tool with steps, as seen in figure 30, would allow for quick response if a product is well within in tolerances or on the verge of being denied for dimensional deviation. The tool is simple with one-millimeter increments from 2mm to 6mm. The tolerance for dimensional deviation varies, but for Renova washbasins it's 4 millimeters for the smaller sized washbasin and 5 millimeters for the larger one, WB36 as an example. It was designed in CATIA and 3D-printed at Geberit.

Figure 30: Step measurement tool

3.1.4 Goods collection

On the 1st and 2nd of November 20 washbasins of model WB36 scrap, reported with open crack was gathered to debunk if the quality control done in production affects the results of dimensional deviation, as only one fault is reported, and open cracks are noticed first. The step measurement tool for dimensional deviation was used. The following week pieces from every mould of washbasin WB36 was collected to compare dimensional deviation across the different moulds, a total of 25 was collected and measured.

3.2 Casting impact factors

3.2.1 Casting parameters

The filling pressure had previously been decreased from 3 bar to 2.7 bar mid-2021 as it was stated filling pressure was applied even though moulds were filled. To test the filling pressure a bucket test introduced from Geberit’s Swedish ceramic factory was used. While filling the mould the air hose from the mould was disconnected and placed in a bucket of water. As slip filled up the mould, air escaped through the hose, producing bubbles in the bucket. The moulds is declared full when no more air is escaping the mould.

The filling pressure is incrementally increased from 1 bar to 3.1 bar which is the end of filling. To experiment the ramp was slowed down from 120 seconds to 200 seconds, meaning a less steep filling curve.

Ceramic specialists carried out multiple tests of the draining and hardening pressures by testing the maximum and minimum pressures to create guidelines. First hardening and draining was simultaneously raised. Hardening from 3.3 bar (330 kPa) to 4.3 bar (430 kPa) and draining from 2.3 bar (230 kPa) to 3 bar (300 kPa). Second test was normal hardening of 3.3 bar and increased draining of 3 bar. Third test was hardening of 4 bar and the draining was configured to be through the bottom outlet of the pieces, first was 3.4 bar then 2 bar. After establishing maximums, the draining and hardening parameters were adjusted until satisfactory results were achieved in the foundry and after casting.

From theory it is known that increased slip temperature will cause faster thickness building when casting ceramics, to test the significance the temperature of the slip was increased from 45°C to 47°C in the slip tanks used for casting toilet bowls and thickness of the pieces was measured according to standards.

3.2.2 Mould position

By analyzing the production results over a month-long period, it could be noted that mould 5 produced more straight goods than mould 8, a distinct difference between the two moulds is the placement in the mould battery. Mould 5 being in the third position from the left had a wait time of two de-mouldings, while mould 8 being in the second to last position waited for 6-7 de-mouldings, depending on how many moulds were being cast. Through discussion with the technical department suspicions of this affecting the dimensional deviation arouse. It was thought that the significantly longer wait time could cause the piece to soften as water from the capillaries could be absorbed back into the piece. Further discussions leaned towards a possible pressure difference when mould filling and applying casting pressure as a result of the distance between the moulds and the pressure source. To investigate and compare the issue pressure-drop calculations according to chapter 2.6 were made. To further try to solve the problem it was suggested to move mould 8 to the beginning of the mould battery, meaning earlier de-moulding and possibly change in mould filling and casting pressure. Due to logistic reasons mould 8 was moved to an earlier position of the second casting machine. The second PCL machine is identical and additional moulds were moved between the machines to match up the casting volume. The move was carried out on the 14th of December, service and acid-treatment was done on the 17th meaning accurate results were expected on the 21st of December. The shuffle would possibly enable increased production volumes of WB36 in the future.

3.3 Handling (Robotics and transport)

3.3.1 De-moulding angle

De-moulding angle referrers to the angle of the support as the robot removes the piece from the mould. The angle was found to differ between mould 5 and mould 8, by watching videos of the de-moulding process. Negligible markings on the inside of the bowl of pieces from mould 8 suggested this problem. From the video it was seen that the piece would fall forward slightly before being caught by the support. The de-moulding motion was reset and programmed for both moulds by a robot technician on the 13th of October (figure 31).

Figure 31: Resetting de-moulding angle

3.3.2 Push function (Tönäisy)

To decrease the amount of dimensional deviation in pieces that occur from a visible bump on the edge or brim of the washbasin the robot was programmed to push the whole brim backwards while the piece was resting in its' support. The motion was conducted with a stiff rubber plate and difference between pushing distances and locations was tested. The same moulds were tested without the push function to determine the effect of the action. Said test was done on the 9^{th} of November and results were gathered after firing on the 15^{th}.

3.3.3 Enhanced de-mould support (Pizza-lapio)

The original de-moulding support holds the piece by the indentations on the backside along with a support around the backside of the brim. In figure 32 below one can see the original support with an added pizza-shovel like support beneath, covered in a rubber matt. The pizza-shovel is thought to provide support for the bottom, while the piece is de-moulded and while resting in the support, in hope to decrease dimensional deviation or unwanted deformation. The pizza-shovel has special-mechanisms designed to de(attach) to the support as it has to be removed when placing the piece on the drying cart. WB36 mould 8 was cast without a pizza-shovel until the 22^{nd} of October.

Figure 32: De-mould support WB36, pizza shovel attached

3.3.4 Drilling

Drilling of the slip feed and drain is done to clear out the uneven edge that remains after casting to avoid cracking when drying or firing. The operation is carried out by the robot and a hollow drill bit that is larger than the original hole.

An increased amount of cracks on the bottom of the pieces were noted on the 1st of December and the origin was found to be the hole for slip feed and drain on mould 7 and 9, by gathering a few test pieces from the affected moulds, seen in figure 33, it was discovered that the hole on mould 9 was off-center and about 8-10mm lower than mould 7, clearly visible in the figure (mould 9 being on the right hand side). The crack went in the opposite direction on mould 7 and mould 9, for most of the pieces.

Figure 33: Cracks from drilled feed hole

To combat the issue the robot was re-programmed, with a new zeroing for the center of mould 9 and a test to run completely without drilling on mould 7, seen in figure 34 below.

Figure 34: Slip feed, undrilled

3.3.5 Transport

Transport at Geberit in Ekenäs occurs as both manual and automated transport. Manual transportation happens in the foundry when drying carts with green pieces are moved to the drying tunnel and in glazing when the drying carts are moved into the glazing cells. Automated transport is carried out by AGVs mentioned in the transportation defects chapter. The AGVs move the kiln-carts from glazing to the oven, during this time the pieces are subject to transport damages (seen in figure 35) from uneven flooring or bad surfaces on the kiln-cart. The uneven flooring and unnecessary long transportation is due to the factory and industry evolving at a rapid phase resulting in re-building and developing production while part of it is still on-going. The plates on the kiln-carts are serviceable and the quality of the surface and gaps between plates varies, as seen in figure 36. To combat transport damages the use of a 1-millimeter layer of cellular foam was placed on the kiln-carts to provide dampening and a more even surface.

Figure 35: Transport damage

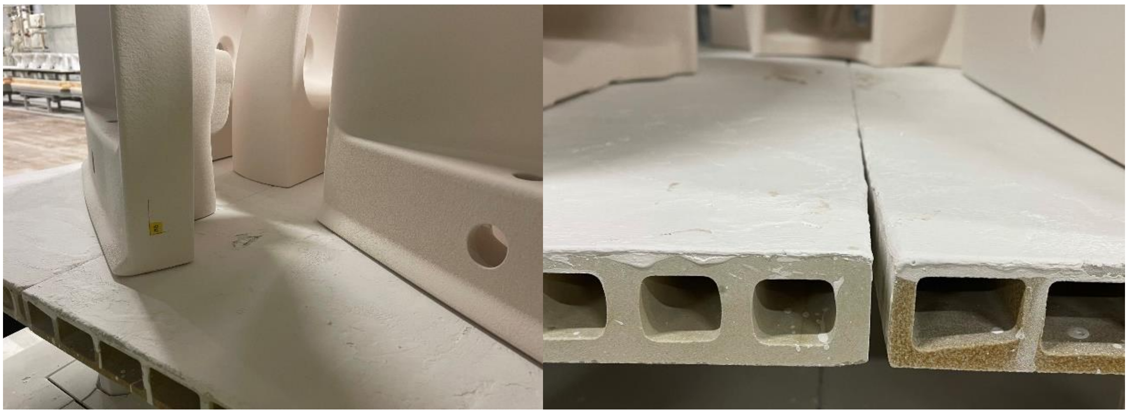

Figure 36: Kiln cart in bad condition

3.4 Ambient conditions

As previously mentioned in the drying chapter, ambient conditions like relative humidity and temperature play a role in the drying rate of a cast piece. The ambient air is constantly monitored, and the temperature and moisture content are adjusted using an air-management system called Unifog. From figure 37 below, one can see the requested values of 55% relative humidity (Rh) and 26,5°C at the right, above shows the current reading.

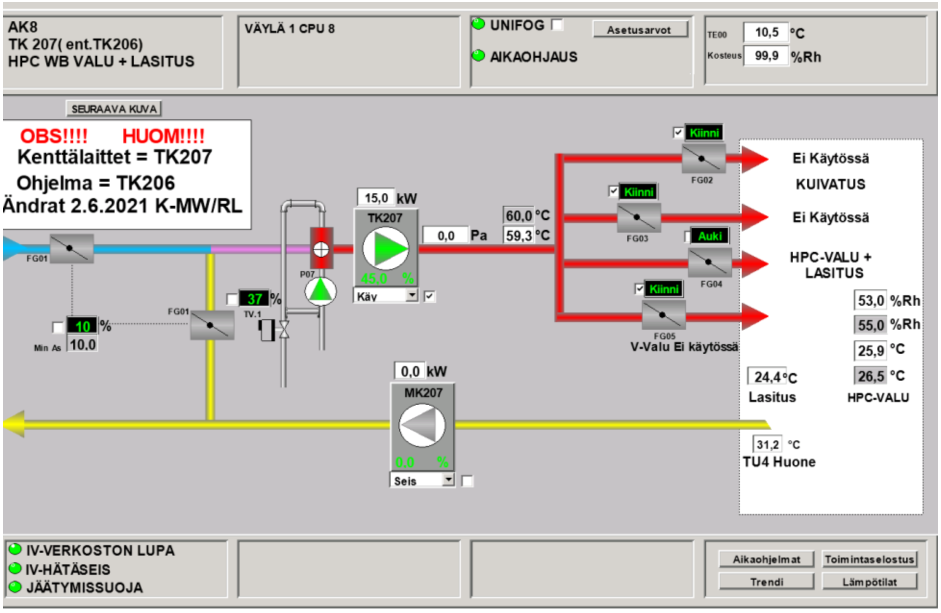

Figure 37: Air-management system's control panel (Source: Henrik Lemberg, Geberit)

To investigate the impact of ambient conditions on a washbasins defects like cracks and dimensional deviation the logged that from the air-management system was analyzed for irregularities. Furthermore, manual measurements with a Vaisala HMI31 humidity and temperature indicator was taken three times a day for a week to compare with automatically logged data.

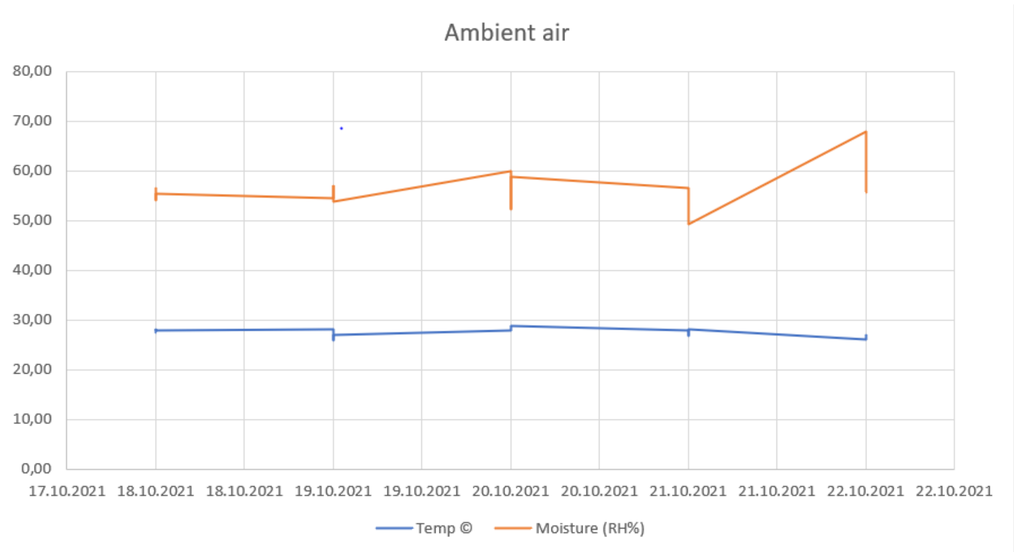

Figure 38: Manual measurement of temperature and humidity

The average ambient temperature measured over the week was 27,52°C and the average humidity was 56,26%Rh. The manual measurements seen in figure 38 correspond with the latter part of figure 39 and the collected data could therefore be deemed accurate.

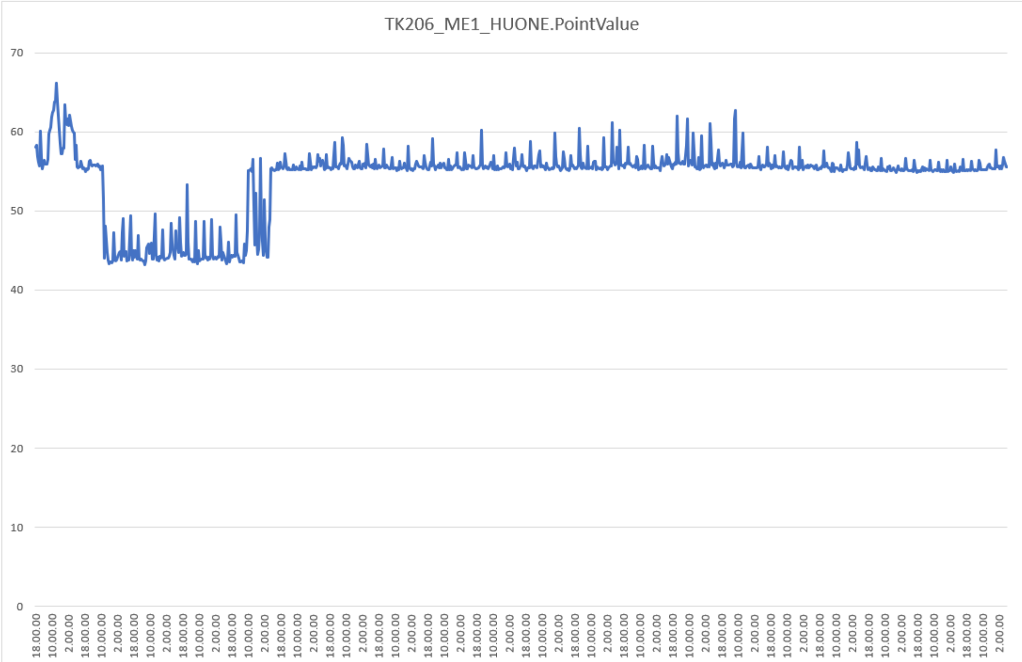

Figure 39: Relative humidity from air-management system

A spike in the ambient moisture content in the washbasin foundry was logged between the 12th of September 8.00 and 13th of September 6.00, the average moisture content was 61,10%Rh over the 22-hour period. The second abnormality seen in figure 39 for the ambient air moisture content in the foundry was logged between the 14th of September 14.00 until 20th of September 10.00. During this time period the average moisture content was 44,79%Rh.

To see if air circulation or air streams affect the drying of the green pieces and possibly the straightness or cracking of washbasins, a tarpaulin tent was used to cover the test batch of a few drying carts. The drying carts were placed within the tent immediately as the cart was full and stored for a day. Following the pre-drying said carts were moved into the drying tunnel as normal procedure.

3.5 Mould design

As it was noticed that dimensional deviation for WB36 grew and became an apparent quality issue the shrinkage compensations were investigated. The first compensations made were symmetrical and said revision was used for mould 3 through mould 5. The symmetrical compensations is seen in figure 40 and 41 as blue. Dimensional deviation remained an issue and further compensations were investigated. The first unsymmetrical compensation seen in figure 40 and 41 as brown was implemented for mould 6 and 7. This compensation would tuck one corner of the brim backwards to counter the slight skewing motion. Both compensations relieved some dimensional deviation but were only straight if the push motion was used. Further unsymmetrical compensations were done, seen in figure 40 and 41 as gray. This compensation pulled the tip of the washbasin in the same direction and had slightly more aggressive compensation of the corner of the brim, compared to the first unsymmetrical compensation. Moulds 8 through 11 were ordered on this revision.

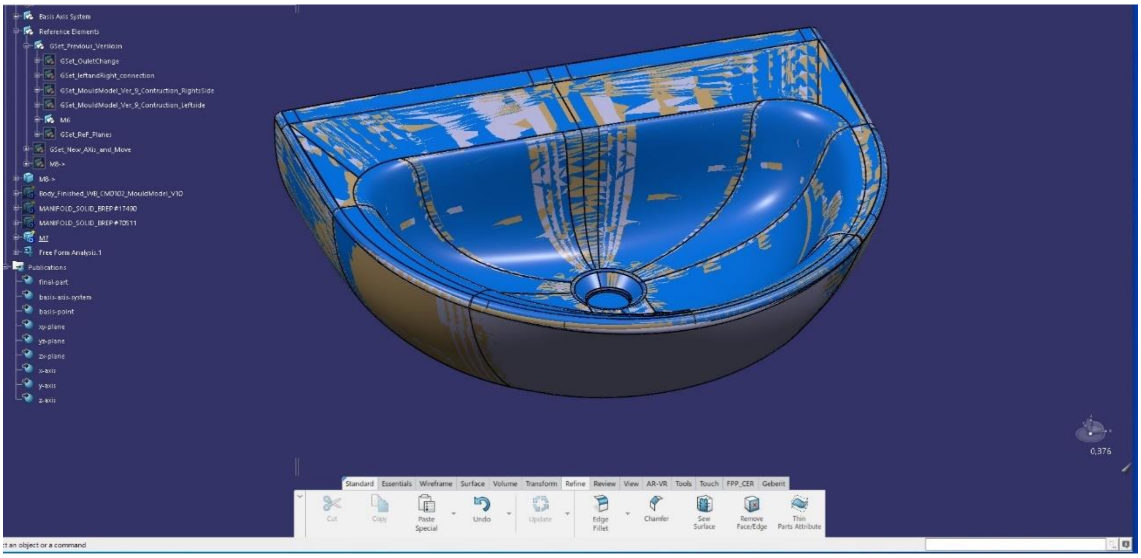

Figure 40: WB36, comparison in Catia

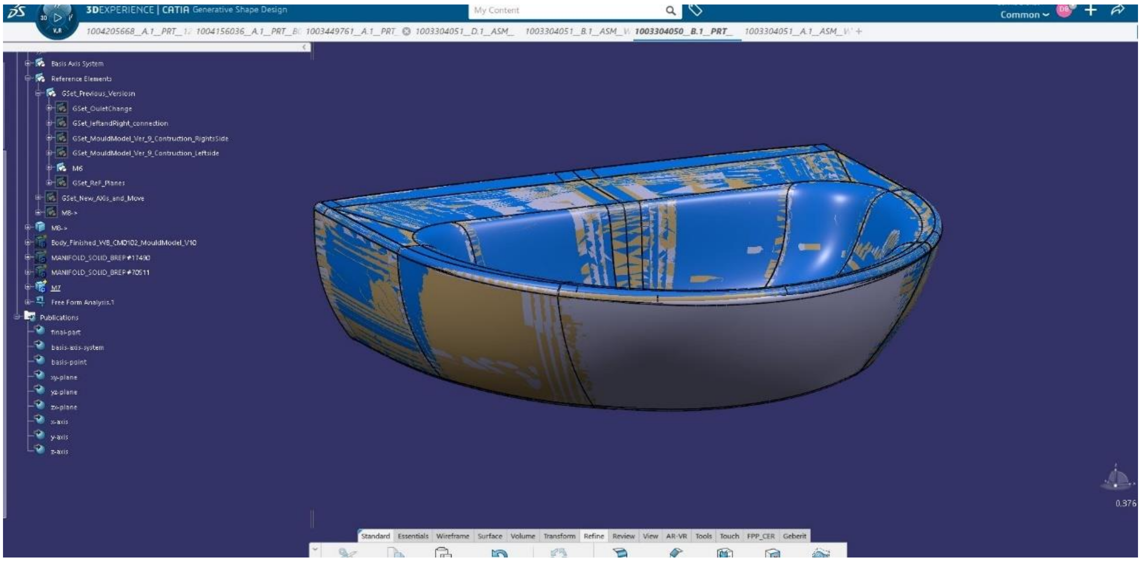

Figure 41: WB36, comparison in Catia(2)

3.6 New slip formula

A test batch of slip from Bromölla, Geberit's ceramic factory in Sweden was used to see if the different clay used in the batch would provide elasticity and cracking resistance to the washbasins in the foundry. Five tanks of slip were casted during two shifts on the 3^{rd} of November. Parameter and quality changes were documented by the ceramic specialists. After the test batch was finished, parameters were returned to old values.

The laboratory and slip production in Ekenäs produced a new slip formula with more ball-clay and less pegmatite in which de-flocculants were used to maintain the same slip parameters (thixotropy, viscosity and density) as the old formula. The new slip is a compromise between Bromölla's slip and Ekenäs' old slip. The slip was put into production in November/December and required major changes in casting parameters to stabilize the production quality.

4 RESULTS

4.1 3D-scan and measurement follow up

Figure 42 shows the computer model (in Creaform) of a fired piece from M5 when 3D scanned. The used 3D scanner is a Creaform Handyscan BLACK 3D with an accuracy of 0.025mm and a measurement resolution of 0.025mm. Results are produced with assumptions the 3D scanner is 100% accurate and repeatable, the scanner's accuracy was not verified on a known measurement.

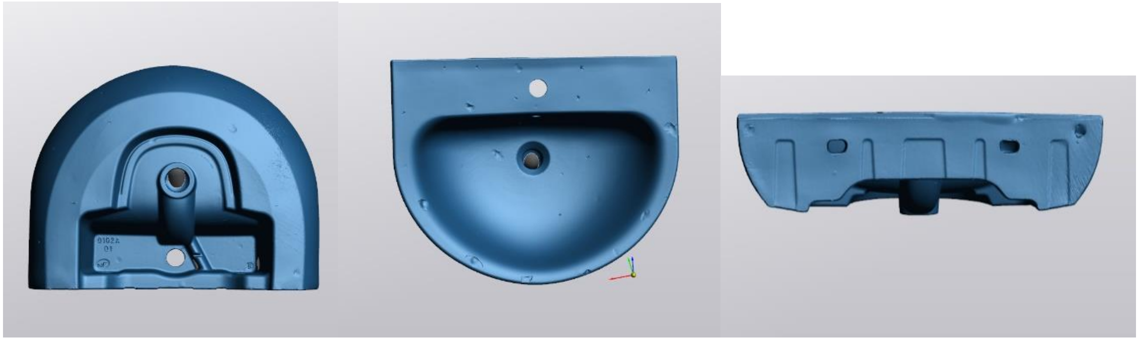

Figure 42: M5 scanned with Creaform Handyscan BLACK 3D

By layering the two scans on each other and using a built-in compare function figure 43 and 44 were produced. From the results one can see noticeable differences in height on the rim because of the added compensation of M9. As M9 produce more dimensional deviation than M5 this can be concerning as the compensation was put in place to counter said defect.

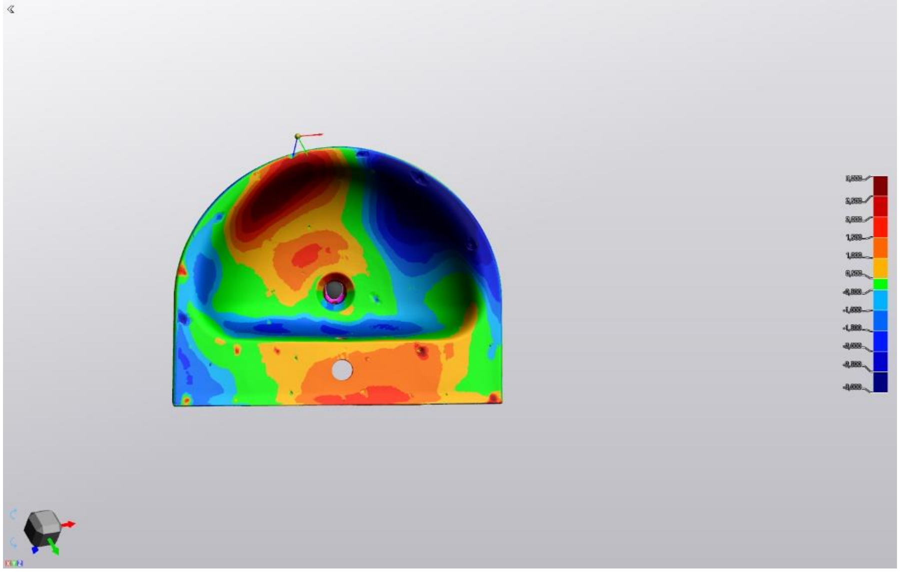

Figure 43: M5 compared to M9

Analysing the back of the products (figure 44) shows that M5 have slight dips in the side compared to M9 and M9 is slightly lower on the brim, however the pieces are more similar overall compared to the frontside.

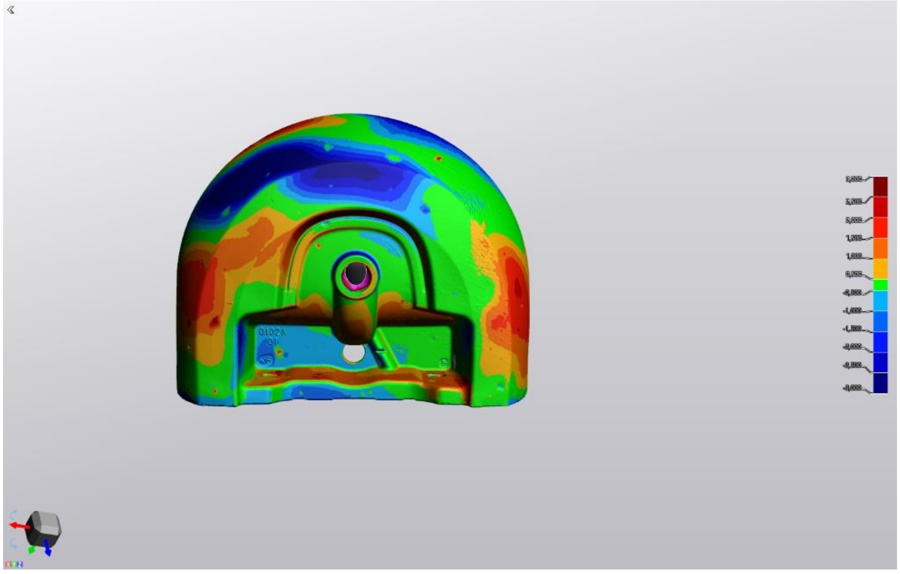

Figure 44: M5 compared to M9

3D-scan of the moulds yielded interesting results when comparing to the CAD-files used when ordering the moulds from external mould producers. In figure 45 one can see the female part of mould 5 compared to its cad-file. The lower part is lower and impossible to match, the male part of the mould is similar to the cad file.

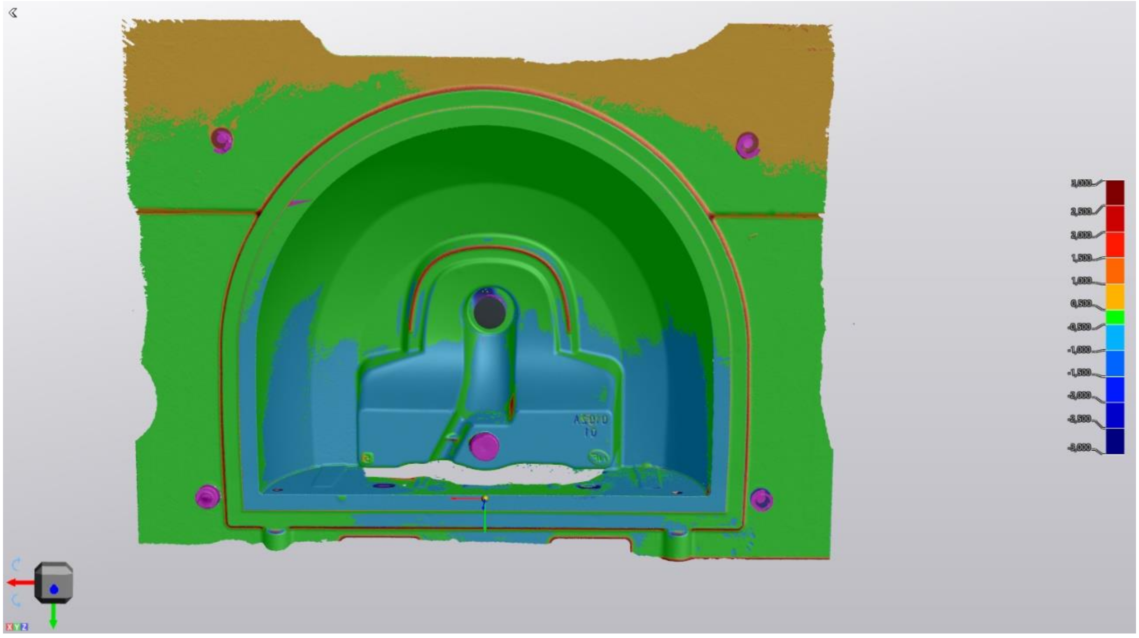

Figure 45: M5-scan compared to cad-file

Mould 6(M6) compared to its cad-files (figure 46) aligns and is identical, when analyzing production results however, M6 produce more dimensional deviation than M5.

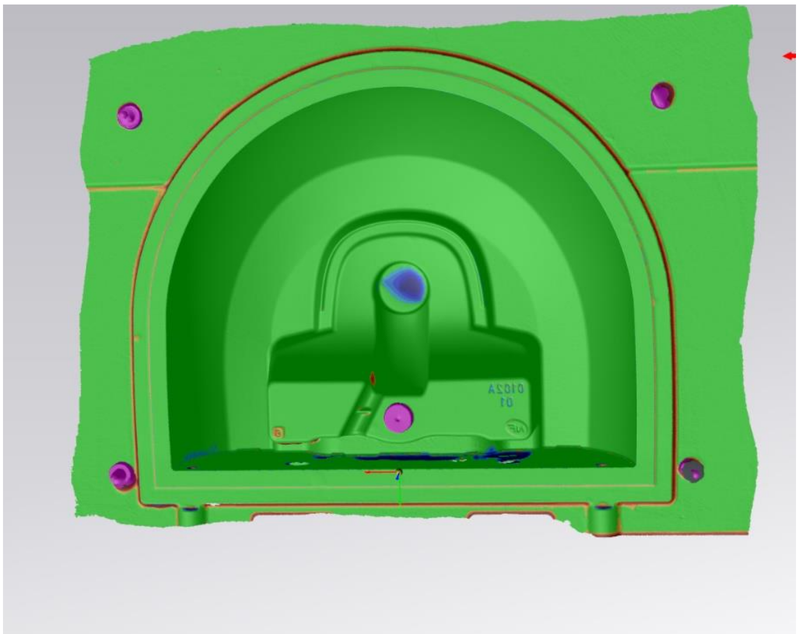

Figure 46: M6-scan compared to cad-file

Measurements taken during the green stage, white stage and after firing showed minor differences in the placement of the drain hole of M5 compared to M9, however after drying the difference had evened out. Drying shrinkage was recorded to be 1.7% for M5 and 2.0% for M9. Total shrinkage recorded was 10.6% and 10.8% respective, which differs from the expected values of around 12%.

The dimensional deviation tool was partly successful and could quickly identify if a piece was straight or skewed enough to be declined. However, a more accurate deviation of the steps, say 0.1mm would be desired as the 4-millimeter step would fit under a 4.1mm and 4.9mm gap. While only the 4.9mm is close to being classified with dimensional deviation. To more accurately measure this, drill bits with varying thickness from 3.8 to 6 millimeter and increments of 0.2millimeters have been used and continue to be a better option, despite being harder to handle due to the size.

4.1.1 Goods collection

Out of the 20 pieces of WB36 reported with open cracks none were skewed out of tolerance (5 millimeters) for dimensional deviation. Six pieces were from M5 and had dimensional deviation of 1-3 millimeters, two pieces were from M8 and had 4 millimeters of dimensional deviation. The remaining 12 pieces that were gathered were from M9 and had ranging dimensional deviation from 2-4 millimeters.

By analyzing gathered washbasins of model 36 from different moulds it was found that M5 had on average 3.5mm dimensional deviation, with a spread of 0.1mm meanwhile M7 had an average of 3.7mm but results between 3mm and 4.5mm. M9 had an average of 2.7mm dimensional deviation and a spread of 1mm on the collected goods, at this time mould 8 and 9 produced most dimensional deviation. While M7 was straight according to measurements the push function was necessary and a bump visible on the brim. M5 was consistent and straight according to quality standards.

4.2 Casting impact factors

4.2.1 Casting parameters

Results from the bucket test lead to the filling pressure being increased to 3.1 bar, to ensure all moulds were properly filled. No direct correlation with dimensional deviation or other defects could be drawn from this test as there had been other parameter changes done during this time.

A slower increase in filling pressure showed a decrease in dimensional deviation as a direct result when analyzing the results from quality control. Slowing down the filling time did not extend the casting cycle time as it could be deducted from the waiting time and allow for filling to begin earlier, instead of waiting for the robot.

The combination of maximum hardening and draining led to the piece cracking on multiple spots. De-moulding was unsuccessful as the drain in the piece itself would stick to the mould. An increased draining pressure with normal hardening showed to produce hairlike cracks from the feeding point of the draining pressure seen in figure 47. More cracks were found on the top side of the brim, in line with the feeding point, it was apparent the pressure blowing on the inside caused cracking to occur in said spot. Decreasing the draining pressure to 2 bar led to poor drainage, more so re-configuring the draining and hardening feed point to the sink hole itself also showed decreased drainage of slip from the piece (see figure 48). Poor drainage led to softness in the bottom of the piece which result in a deformation seen in figure 19.


Figure 47: Hairlike crack from pressure feed (Source: Robert Kallström)

Figure 48: Poor drainage (Source: Robert Kallström)

Draining pressure was set to assure proper drainage of the piece and hardening was set to the highest pressure before cracking appeared in the foundry. Hardening was lowered marginally (0.2 bar) as cracks were found after drying. Through testing it was found that hardening affects dimensional deviation. When hardening is insufficient or draining is poor the piece is soft and therefore lead to dimensional deviation or other deformation.

The ceramic specialists have actively followed up production reports and done small changes to filling, draining and hardening times and pressures to improve quality of product. These have shown improved results however the lack of documentation means the results of which parameter change is right cannot be confirmed.

Increasing the slip temperature in the slip tanks by 2 °C provided an increased casting thickness of 0.2 mm, this change is small and therefore no further test was done on the washbasin foundry.

4.2.2 Mould position

The length and diameter of the tubing between the mould and the rigid metal piping is the same for the moulds. The distance between the valve and the first mould is 240 cm, and between mould there is 40 cm rigid piping. The diameter of the rigid piping is 61 mm (R

= 30.5mm) and 38 mm on the neck leading to the individual tubing. Viscosity (ɳ) used for the slip is 350 mPas and the volumetric flow rate (Q) supplied by the Sandpiper S20 is 750 liters per minute (12.5 $\frac{l}{s}$). The length and diameters for individual moulds cancel out and the remaining length is between the moulds, the biggest possible pressure loss is between mould 1 and mould 10, giving length (L) of 360 cm. Placing these into Equation 5 gives :

$$\Delta P = \frac{8 \cdot 0{,}35 Pas \cdot 3{,}6m \cdot 12.5(\frac{l}{s})}{\pi \cdot 0.0305 m^4}$$

$$\Delta P = \frac{8 \cdot 0{,}35(\frac{N}{m^2})s \cdot 3{,}6m \cdot 0.0125(\frac{m^3}{s})}{\pi \cdot 0.0305 m^4}$$

$$\Delta P = 1.315 Pa = 1.315 \cdot 10^{-5}\ bar$$

Complications arouse as the mould positions were changed, challenging results with the quality for all washbasins were stabilized after minor parameter adjustments. WB36 has shown better results with an average yield improvement from 60% to 80-85%. WB 34 was moved from battery 102 to 101, challenges with quality apparent (dimensional deviation). WB38 was not moved but experienced quality challenges (dimensional deviation) to the point it was taken out of production until further investigation. As production volume for WB36 is larger compared to other models the overall yield for washbasins was 75% in the end of December and 75-80% in February (a lot of challenges in January).

4.3 Handling (Robotics and transport)

With the de-moulding angle re-programmed, the piece released from the mould easier and no marks on the inner surface was seen, the de-moulding angle however did not affect the dimensional deviation problem seen with the WB36.

Push-function (Tönäisy) was found to have limited but positive impact on dimensional deviation. By pushing the brim at 13-14 o'clock (or where the bump would appear) for

15-20mm, the dimensional deviation improved by roughly 1 millimeter. This resulted in pieces that were on the verge of being too skewed (3-5mm) could be saved. The bump was still visible to the trained eye, but the pieces were within product specifications. Products that had dimensional deviation of 1-3mm saw no improvement of the push-function.

The addition of a pizza-shovel did show improvements regarding dimensional deviation in the results and provided visibly more support when examining the de-moulding process. However, the results continue to vary for the different moulds even though the de-moulding conditions are similar. This suggests that the main reason for dimensional deviation is something else. Through further examination it was also noted that the bottom of the pieces contained more moisture when the pizza-shovel was installed. This resulted in an increase of cracks in the bottom and a new revision of the pizza-shovel with strips of rubber that allow for water to escape was made.

By adjusting the drilling of mould 9 and running a test on mould 7 without drilling, the results showed a significant improvement for both moulds. This concluded that the offset drilling of mould 9 led to the hole being too close to the edge of the product and therefore easier to crack, by readjusting the center of the drilling operation the hole was now in the correct position. The removal of drilling on mould 7 decreased the number of cracks from the bottom. However, to ensure continuingly improved results, the drilling was reinstated and carefully adjusted and yielded the same results as mould 9. When analyzing the direction of the crack from the feed and drain hole it can be seen that if the drilling was offset to one direction the crack went in the opposite direction, demonstrated in figure 47 below.

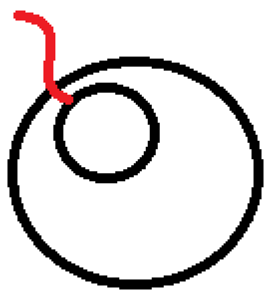

Figure 49: Crack direction(red) depending on the drilling offset from feed

It was found that the quality of the kiln-carts' plates varied and could cause transport damage to the products, plates with worse damaged surfaces could also cause the piece to grab while being handled by the robot. Dents in the flooring and gaps between different types of flooring was found to cause wiggling motions on the carts that could possibly cause transport damages. Cell-foam proved to provide slight dampening and a more even surface on the kiln-cart and reduced transport damages for Renova 36. No direct correlation with dimensional deviation was found.

4.4 Ambient conditions

With the average delay of four days until changes can be noticed from the hydra-reports done by the in-process quality control a graph was generated from the 7th of September until the 29th of September. Analyzing the 3-week period seen in figure 48 of the dimensional deviation and open crack scrap relative to the fire total increase around the time of the abnormality. However, the four-day delay would suggest the changes should take place between the 18th of September and 24th of September for the low-moisture period. The spike above 60%Rh between the 12th and 13th of September may have caused the increase in dimensional deviation seen on the 16th and 17th of September. The increased ambient moisture would cause the pieces to dry slower during their waiting period within the foundry – as predicted by the literature. A lower ambient moisture content than the requested 55% lead to no noticeable change in dimensional deviation.

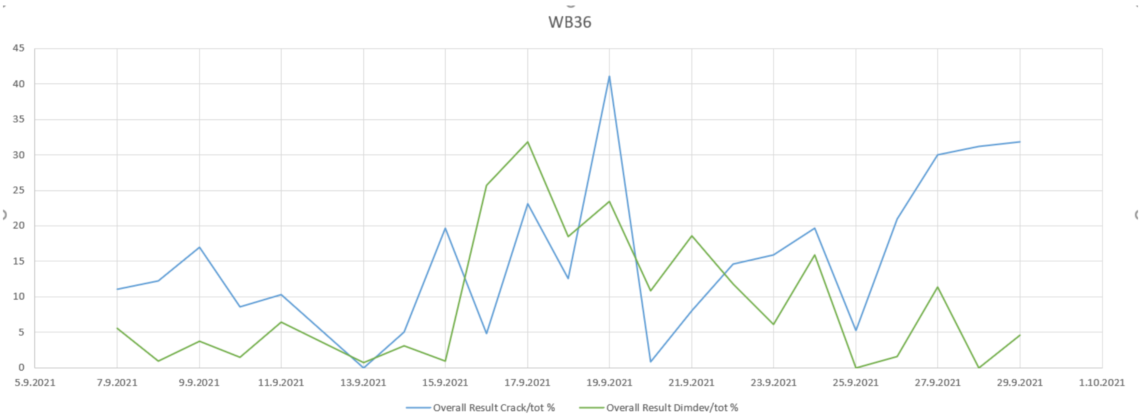

Figure 50: Percentage of crack/dimensional deviation over total amount of fired WB36

The amount of reported open cracks peek around the abnormality and decrease to 2 reported open cracks out of 230 fired on the 20th of September. However, an immediate upward trend on the number of open cracks continue until the 1st of October, as seen in figure 49, despite the ambient moisture content remaining stable around the 55-56%Rh average. The peak of above 70% cracked goods on the 11th of September is an error in the graph as it cannot be seen in previous figure, possibly due to an increased amount of re-fired goods being scrapped resulting in double reports in the system.

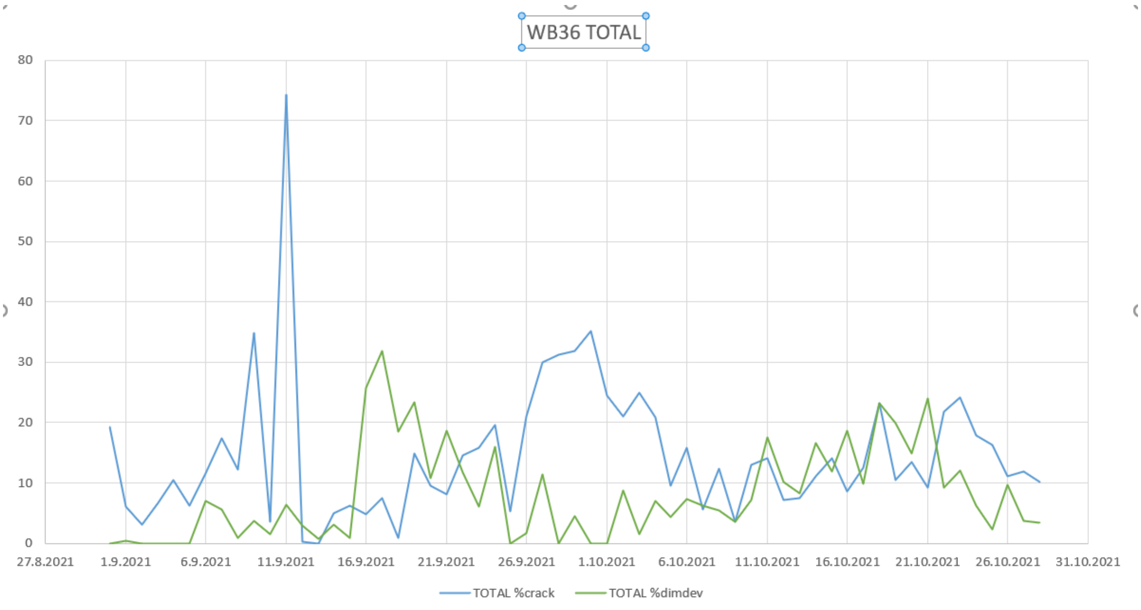

Figure 51: Percentage of crack/dimensional deviation, expanded graph

Between the 26th of September and 6th of October the number of reported dimensional deviation is seemingly low, this however can be a result of the higher number of reported open cracks as the system allows for one fault to be registered and the procedure for quality control would lead to the crack being discovered first.

The pre-drying of washbasins in the tarpaulin tent showed no noticeable change in dimensional deviation, however cracks along the solid and hollow edge showed to be smaller before firing. After firing the same cracking occurred whether the pieces had been dried in the tent or not.

4.5 Mould design

The first symmetrically compensated moulds for WB 36 were moulds 3-5 which at the beginning of casting showed signs of dimensional deviation. This was partially solved with the earlier mentioned push function; however further compensations were necessary. Mould 7,8 and 9 produced dimensional deviation periodically and were stabilized with push function. It was thought that the compensation was insufficient, but results improved slightly. Following the shuffle of moulds in previous test for mould position along with slip recipe change, the WB36 showed to have minimal dimensional deviation whereas the yield for uncompensated moulds WB34 and WB 38 dropped without explanation, WB35(also uncompensated) however continuingly produced great results.

4.6 New slip formula

As the new slip was put into production it was quickly noticed that the thixotropy was difficult to maintain at desired level, even with additives. However, the increased thixotropy yielded positive results for WB44 which previously had problematic cracking between the hollow and solid cast edge. Dimensional deviation rouse for WB34 and WB38 which had never been skewed before, meanwhile WB36 was straight, with open cracks as the biggest reported fault.

4.7 Priority and focus

By arranging the problems according to weight and scoring them from 1 to 5 on different factors, one can decide where to prioritize and direct focus when solving quality challenges.

Table 1

Factor	Weight	Cracking	Dimensional deviation	Pin holing	Glazing faults
Quality grade	0.2	5	5	1	2

Fault volume	0.3	5	3	2	2
Effect on production volume	0.3	3	4	1	2
Repetitiveness	0.2	2	3	2	4
Focus value		3.8	3.7	1.5	2.4

Quality grade is between rejected (5) and easily repairable (1), carrying a weight of 20%. A score of 2 would indicate it is repairable majority of the time. Fault volume refers to affected models, 5 being all models and 1 being one or a few models, with a weight of 30%. Affected production volume is weighted at 30% and regards if the fault has major (5) to minor (1) impact on the total production volume of washbasins, models with multiple moulds in production suffering from similar faults would score higher. Repetitiveness (20%) provides a score regarding the traceability of the issue as this affects the difficulty in finding solution – a higher score mean it's repeatable (5) and therefore can be solved. Random (1) means speculations and further testing is required to solve the problem which is time consuming.

5 DISCUSSION

As mentioned, the on-going pressure of achieving results quickly means there a lot of operators and technicians making changes to the casting parameters, firing curves and other factors that impact the quality of the end product. To produce valuable test-results only one factor needs to be addressed at a time and this requires a minimum of 4 days of production time which is not always available. Table 1 shows that focus should be placed in solving cracking and dimensional deviation before solving glazing issues as an example. This as a result of the impact on production volume and rejected goods.

The Creaform 3D scanner was assumed to be 100% accurate, without verification, the 0.025mm accuracy stated by the company and the 99% match with CAD-file of mould 6 enforces the assumption. By verifying the accuracy of the 3D scanner, the validity of the results could be increased.

Extra support when de-moulding showed to have a positive impact. Through discussion with professionals, it was found that other ceramic factories within the organization utilize pre-driers and bigger supports for the initial green drying stage, however, this would require total foundry redesign. The mould re-design involving an unsymmetrical compensation proved to affect dimensional deviation, further improvements can be made to provide integrated support for the heavier pieces as seen when comparing WB64 and WB36. Figure 50 shows a difference between model WB64 and WB36 regarding the support beneath the faucet plane and pool, the weight of the WB36 could benefit from similar supports.

Figure 52: Comparison WB64 and WB36

Pressure drop between the moulds was insignificant at 0,01 mBar. Calculations assumed every mould was the same model, it is worth noting that the slip volume can vary between models. The change in mould position showed a change in quality that could be a result of a change in waiting time. However, as moulds were also interchanged between the two casting machines the total volume and possible mechanical differences between the machines could have impacted the results.

The ambient conditions could have been impacted by on-going renovations and construction work as the wall between the foundry and construction site was torn down and possibly affected temperature, humidity, and air flow. However, the collected data and results aligned with the theory.

When implementing the new slip, a lot of parameters were changed to achieve acceptable production results, as a concoction of changes were made no single parameter that improved result can be decided. The improved results for WB44 could be from increased thixotropy.

6 CONCLUSIONS AND RECOMMENDATIONS

By gathering information and describing the process of high-pressure casting ceramics, more specifically sanitaryware and washbasins it can be concluded that a concoction of factors affect the quality of the product. Relevant data was collected from previous testing done at the factory, discussions and performed tests. By analyzing said data it was found that marginal changes in casting parameters affect end quality. With hardness and dryness of the product being the biggest impact factors for dimensional deviation and deformation, too much hardness however cause cracking at different stages of the manufacturing process. Furthermore, ambient conditions and its' effect on drying shows the importance of a properly functioning temperature and humidity management system. As dry ambient conditions lead to increased risk of cracking.

No direct solution has been found regarding dimensional deviation, the adjustment of demoulding angle and addition of support in the form of a pizza shovel proved helpful. Unsymmetrical compensation improved results in regard to WB36, however the root of the problem lies somewhere else. Additional support in the design could support the weight better. Further investigation of redesigning the de-moulding supports to provide extra support all around the washbasin should be conducted.

The factory operates 24/7 with its' 5-shift system, leading to 5 different operators along with technicians from the technical department adjusting parameters of both casting machines and kilns. To eliminate unknown parameter changes in the foundry it would be suggested that a computer or tablet is installed. With a simple application where casting machine, mould and all parameters are shown and the change in parameters can be reported. The application would then log the date and time with change made into a file that can be inspected later if positive or negative changes in production occur. Improved testing procedures and the means of communication between different parties would allow for more valuable test results.

After the experiment period ended, further improvements were made to the casting parameters in the foundry. The casting ramp was extended (increased time for casting pressure) while the maximum casting pressure was lowered. Furthermore, the draining time was decreased. A shorter draining time minimized water backtracking from the capillarity back into the piece. Hardening pressure was increased and hardening time was decreased. These changes proved very successful as the pieces were drier, with minimal dimensional deviation and cracking.

It is of interest that further studies are conducted on the consistency of slip parameters within slip production and the quality of raw materials. The quality of the produced ceramics vary, even without explanation like parameter changes in casting or firing.

7 SWEDISH EXTENDED ABSTRACT (SAMMANDRAG)

Introduktion

Examensarbetets målsättning är att analysera och dokumentera de faktorer som påverkar kvaliteten av högtrycksgjutna tvättställ vid Geberits fabrik i Ekenäs, Finland. Fokus inom avhandlingen ligger på det problem som uppstått då interna kvalitetskrav blivit allt striktare. Majoriteten av defekter och faktorer som påverkar kvaliteten diskuteras då vissa lösningar gjorda i produktionen kan ha en reaktion i att andra delmoment i produktionen.

Litteraturrecension

Keramik

Lera var ett viktigt byggnadsmaterial i det forna Egypten, Assyrien och Mesopotamien. Keramik avser fasta föremål som bildas av oorganiska föreningar, jordnära råvaror och värme. Sanitetsartiklar eller sanitetsporslin är keramik artiklar som består av toaletter, tvättställ, bidéer och badkar.

Råmaterial och massa

Sanitetsartiklar innehåller huvudsakligen mineralblandningar, med några få huvudkomponenter och många mindre. Råvarorna som används i sanitetsporslin kan delas in i plastiska och oplastiska råvaror. En massa är en vattenhaltig suspension, där den använda råvaran späds i vatten. Egenskaperna hos massan kan sedan manipuleras ytterligare med flockningsmedel för att uppnå önskad viskositet, densitet, tixotropi och permeabilitet.

Plastiska råmaterial

Plastiska råvarorna är ofta en blandning av lermaterial. Produktens plasticitet är dess förmåga att motstå sprickbildning när yttre krafter appliceras. Det är också förmågan att bevara den nya formen när inre krafter avlägsnas. Plastiska råvaror saktar ner torkning och minskar vattenupptaget i det gröna stadiet. De vanligaste plastråvarorna i den keramiska massan är lera (eng. ball clay) och kaolin.

Oplastiska råmaterial

Oplastiska råvaror används för att tunna ut en alltför plastisk massa. Fältspat, kvarts, flinta och chamotte är de hårda råvarorna som används i sanitetsprodukter. Tilläggningen gör det lättare för vatten att avlägsnas från massa. Oplastiska råmaterial ökar vattenupptagning i det gröna stadiet vilket innebär mindre torkstyrka.

Massaparametrar

Massaparametrar så som viskositet, tixotropi, permeabilitet, densitet och porositet uppmäts och justeras enligt behov vid laboratoriet i fabriken.

Viskositet kan beskrivas som motverkan på flöde eller motståndet för en vätska att ändra form eller röra sig och har därav påverkan på hur lätt ett flytande material kan transporteras i rör eller i till exempel formar för gjut.

Tixotropi beskrivs som den gel-lika karaktären som målfärg har, var den är flytande då den är skakad eller omrörd men stelnar då den är stilla. Tixotropin i massan uppstår från leran

Permeabilitet uppmäts som gjuthastighet då de gäller högtrycksgjutning av keramik men representerar ett poröst materials förmåga att göra sig av med vätska.

Densitet är ett materials massa per volymenhet, vanligt är gram per kubikcentimeter men inom keramiken används litervikt och enheter gram per liter.

Porositet är procenten av tomrum i ett material.

Torkhastighet är den hastighet med vilken den önskade fuktnivån i pjäsen uppnås. En långsam torkhastighet innebär att processtiden ökar eller att keramiken är för blöt, en snabbare torkhastighet kan leda till sprickbildning under torkningsfasen.

Gjuthastigheten eller gjuttjockleken för den keramiska massan är den hastighet med vilken den keramiska kroppens väggar bildas i formen.

Gjutning, tillverkningsprocess

Gjutning är en tillverkningsprocess där flytande material hälls i ett tomrum i en form. Efter härdning och stelning avlägsnas biten från formen för sekundära operationer eller direkt användning som produkt. Faktorer som påverkar valet av gjutmetod är kvalitet, kostnad och miljöeffekter. Investeringsgjutning eller vaxgjutning är där ett mönster av delen först görs av vax. Smältmetall hälls sedan i skalet och efter att metallen stelnat bryts skalet för att avforma produkten. Permanent formgjutning innebär att man häller material i en form och extraherar produkten utan att skada själva formen.

Högtrycks gjut

Formning och formdesign

När man designar en form för gjutning, speciellt keramik, måste man ta hänsyn till krympningen som uppstår. Krympning vid keramisk gjutning sker under torkningsfasen och under bränningsskedet.

Formarna som används vid Geberits fabrik i Ekenäs är gjorda av en polymerblandning som tål en massa på upp till 50 grader celsius. Materialet är poröst och gör att vattnet från massan kan absorberas.

Gjutprocessen

Högtrycksgjutning är en tillverkningsmetod som tar bort vatten från den keramiska massan med att pressa det genom formens väggar. Detta uppnås genom att applicera ett gjuttryck på massatillförseln, vid högtrycksgjutning är det vanligtvis över 10 bar. Vatten kan då strömma ut genom kapillären i formmaterialet. Detta gör att massan kan fastna på väggen och bilda tjocklek.

I korthet sker gjutcyklen på följande sätt (se figur 8):

- Formbatteriet stängs och mottryck som håller ihop batteriet fås med en hydraulisk cylinder
- Sandpiper S20 pumpar massa in i formarna via enskilda munstycken till vardera formen

- Då fyllningstrycket är uppnått övergår cykeln till tjockleksbildning med ett tryck på 10.5-11 bar
- Tömning sker med tömningstryck från motstående sida av tvättställen, då en tillräcklig tjocklek är uppnådd
- Efter tömning börjar härdning i form av ett lufttryck från tömningskanalen (ca 3bar), härdningen pressar materialet mot formen ytterligare och den torkar
- Vid formöppning släpper cylindern trycket på batteriet och första formen i batteriet öppnas av traversen
- Roboten avformar tvättstället med individuella avformningsstöd för varje form och placerar dem i torkbordet
- Formen tvättas med vatten, luft och vakuum varefter den stängs och nollställs för nästa cykel

Torkning

Torkning sker när vatten i materialet avdunstar och försvinner från ytan i materialet genom värme från omgivningen som följd av konvektion, överföring eller strålning. Torkningen börjar då pjäsen tas ur formen och kan ta från 6 till 18 timmar. Vid keramisk gjutning har vattenavdunstning visat sig påverkas luftflöde, temperatur och luftfuktighet. Pjäsens arbetsbarhet är maximal under det gröna stadiet, vilket möjliggör finputsning som att ta bort märken eller vassa hörn med en svamp.

Krympning i torkningsskedet är den storleksminskning som uppstår när materialet torkar. Största delen av krympningen sker under det gröna stadiet, mer specifikt har det noterats att märkbar torkningskrympning sker tills fukthalten i pjäsen är 13 %.

Bränning

Bränning är den del av tillverkningsprocessen där den keramiska produkten utsätts för extrem värme. Då sker en förändring i volym, förändring i ytan och smältning av mineralkomponenter i keramiken. Bränningsprocessen orsakar kristallomvandlingar med bildning av nya faser och en minskning av permeabiliteten tillsammans med ökad stryka i produkten.

Bränning vid Geberit sker i ugnar, TU2 och TU4 (förkortning av tunnelugn) är tunnelugnar med kontinuerligt flöde som används för den första bränningen. Ombränning sker i en kammarugn och TU4. TU2 är en av de ursprungliga ugnarna i fabriken medan TU4 är en modernare ugn. Båda ugnarna styrs av en bränntemperaturkurva och genomfartshastighet. TU4 har en modifierad bränningskurva för att hantera första bränning- och ombränningssprodukter.

Bränning av sanitetsprodukter är uppdelad i tre steg. Uppvärmning, hållning vid maximal temperatur och kylning, detta styrs av den tidigare nämnda bränningskurvan. Uppvärmning innebär att temperaturen höjs från omgivningens temperatur till cirka 1200 °C, nästa steg håller sedan max temperaturen innan kylningen påbörjas. Ökningens aggressivitet och längden på hållningen bestäms av företagets specifikationer och produktkrav.

Produktfel och defekter

Gjut defekter

Den automatiserade högtrycksgjutmetoden är problematisk när det gäller korrigering av gjutdefekter jämfört med lågtrycksgjutning där de flesta problem kan repareras på efterhand. Gjutfel kan förekomma under hela gjutskedet; från att fylla formen, stelning av massa, härdning och avformning.

Gjutfel uppstår som:

- sprickor
- hålrum, ihåligheter och separation
- valk
- deformation och skevhet

Tork defekter

Sprickor är den vanligaste defekten som uppstår under torkning. Omgivningsförhållanden som luftfuktighet och temperatur påverkar torkningen. Alltför snabb avdunstning av fukt från produkten resulterar i inre spänningar på grund av att godset krymper. Med korrekta torkcykler bör torkningskrympningen vara över innan aktivtorkning påbörjas. Om omgivningsförhållandena inte uppfylls, rekommenderas att begränsa luftcirkulationen eller täcka materialen med plast.

Glaserings defekter

Glaseringsfel kan ofta upptäckas omedelbart och repareras för att undvika problem med kvaliteten. Defekter med glasyren kan uppstå om själva glasyren är defekt eller appliceringen är felaktig. Utan kontinuitet är defekter svåra att lösa definitivt. Glasering gjord av en robot möjliggör kontinuitet och definitiva lösningar när problem har identifierats. Robotglasering kräver dock kvalitetskontroller eftersom roboten själv inte kan upptäcka defekter.

Glaserings defekter uppstår som:

- Dålig yta

- Små sprickor i glasyrskiktet

- Exfoliering

Brännings defekter

Bränning kan förvärra defekter som redan finns i produkten från tidigare stadier. Nya defekter kan också uppstå under uppvärmning och kylning, på grund av den mineralogiska omvandling som pjäsen utsätts för.

Bränningsfel uppstår som:

- sprickor och kylsprickor

- deformation

- färgning och nålstick

- glasyrkrympning och krackelering

Metod

För att undersöka, kategorisera och kvantifiera orsakerna till de olika defekter som drabbar tvättställ under produktion gjordes följande experiment.

Mätningar och 3D-skanningar

- Tvättställ från två olika formar (form 5 och form 9) mättes efter varje delprocess i produktionen och resultat mellan formarna jämfördes. Samma produkter 3D-skannades med en Creaform Handyscan och jämfördes på dator

Gjutparametrar

- Olika fyllningstryck, härdningstryck och tömningstryck prövades för att se vilken inverkan de hade på gjutresultatet
- Ökning på massa temperaturen från 45 till 47 grader resulterade i 0.2mm ökad väggtjocklek

Robotfunktioner som avformning, buffning och borrning

- Avformningsvinkeln justerades och pizza-spade installerades på avformningsstödet för att öka stödfunktionen
- Buffning av övre kanten av tvättstället på olika platser prövades i hopp om att minska skevhet
- Borrning av tömningshålet justerades och det testades även på att ta bort den helt eftersom det uppstod bottensprickor från hålet

Omgivningens temperatur och fuktighetshalt

- Omgivningens temperatur och fuktighetshalt uppmättes manuellt och jämfördes med loggade data från luftkontrollsystemet. Avvikelser i luftfuktigheten jämfördes med produktionsresultat

Kompensation av form

- Eftersom tidiga revisioner av WB36 formar drabbats av skevhet(deformation) gjordes osymmetriska kompensationer i formdesign för att motarbeta denna defekt

Ny massa recept

- En testmassa från Bromölla, Geberits fabrik i Sverige provkördes för att se ifall en annan sorts lera skulle hjälpa med sprickbildningen i gjuteriet
- Laboratoriet i Ekenäs producerade en ny egen massa me 2% mera lera som en kompromiss mellan den gamla massan och testmassan från Bromölla

Resultat

Mätningar och 3D-skanningar visade skillnader på produkterna från form 5 och form 9, det visade sig även att form 5 inte matchade sin CAD-fil till 100%. 3D-skanningarna antogs vara 100% repetitiva, men verifierades inte med något känt föremål.

En långsammare fyllningsramp visade sig minska skevheten, en långsammare ramp påverkade inte produktionen tidsmässigt efter som denna kunde reduceras från väntetiden. Härdning och tömning ledde till sprickbildning då de var fel inställda.

En förbättring på avformningsvinkel för form 8 visade sig nödvändig eftersom den var några grader fel. Buffningsfunktionen utförd av roboten kunde rädda tvättställ som var på gränsen till för skeva (mellan 3-5mm) men hade ingen större inverkan på tvättställ mellan 1-3mm skevhet.

Pizza-spaden gav extra stöd och minskade skevheten en del, dock förhindrade pizza-spaden vattnet att rymma ur bottnen från tvättställen vilket kunde öka sprickbildningen, en ny revision men räfflat botten förbättrade situationen.

Borrningen visade sig hjälpa med sprickbildning från fyllningskanalen såvida den var rätt placerad, då den var icke-centrerad bildades sprickor även från de borrade hålet.

Kast i luftfuktighet påverkade torkningshastigheten av gjutna produkter direkt, en lägre luftfuktighet ledde till försnabbad torkning och således en ökning i sprickbildning.

Inga direkta förbättringar syntes av den osymmetriska kompensationen i formarna men med hjälp av buff-funktionen kunde dessa stabiliseras och senare visade sig kompensationen minska skevheten till en viss grad.

Den nya massan var problematisk till en början och det noterades att tixotropin var svår kontrollerad även med tillsatsämnen. Ökad tixotropi gav bättre resultat för WB44 som ofta haft sprickbildning men skevhet ökade i WB34 och WB38 som tidigare varit raka.

Genom att arrangera och väga de olika felen gjordes en prioritet- och fokustabell.

Diskussion och sammanfattning

Fokus bör läggas på att lösa sprickor och dimensionsavvikelser innan man löser glaseringsproblem som exempel. Extra stöd vid avformning visade sig ha en positiv effekt på kvaliteten. Andra fabriker inom organisationen använder förtorkar och större stöd för den inledande torkningen i gröna stadiet, detta skulle kräva total omkonstruktion av gjuteriet för att lyckas. För att producera värdefulla testresultat måste fokus vid test ligga på endast en faktor då kan man lättare identifiera problem som uppstår.

Produktens hårdhet och torrhet är de största påverkande faktorerna för dimensionsavvikelser(skevhet) och deformation, för hög hårdhet orsakar dock sprickor i olika skeden av tillverkningsprocessen. Ingen direkt lösning har hittats beträffande skevhet, justering av avformningsvinkel och tillägg av stöd i form av en pizzaskyffel visade sig vara till hjälp. Förbättrade testprocedurer och kommunikationsmedel mellan olika parter skulle möjliggöra mer värdefulla testresultat.

Det är av intresse att ytterligare studier utförs på kontinuiteten av massaparametrar inom massatillverkning och kvaliteten på råvaror.

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