DEVELOPMENT OF PAPERBOARD CUP MANUFACTURING CHAIN MONITORING AND ANALYSIS

Lappeenranta–Lahti University of Technology LUT

Master’s thesis in mechanical engineering

2023

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ABSTRACT

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Development of paperboard cup manufacturing chain monitoring and analysis

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68 pages, 41 figures and 6 tables

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Keywords: Paper cup, paperboard cup, disposable cup, cup forming, monitoring, analysis

The goal of this master's thesis was to develop the monitoring and analysis processes utilized in the research of paper cup materials and manufacturing processes. The thesis consists of a literature review on the paper cup manufacturing process, modern cup materials and cup machines, followed by a practical section of cup manufacturing trial runs, during which multiple monitoring and analysis methods were trialed. The cup type used in the trials is a barrier coated paperboard hot cup with a volume of 250 ml.

In the practical stage of the thesis, a high-speed cup machine was used to form eight reference paperboard materials and three experimental materials with varying coatings into cups. The main goal of the trial run was to find repeatable process parameters for each material and to test the viability of different monitoring methods during cup manufacturing. The cups acquired from the trial runs were used to test different methods for the analysis of finished cups. For nearly all the tested materials, process parameters resulting in good cups could be found. Some materials suffered from runnability problems possibly related to friction, heat, or a combination of the two. All found process parameters were logical and the runnability of the experimental materials was found to be comparable to their commercial alternatives.

Most of the trialed cup analysis methods were deemed viable, although some felt excessive or didn't get enough attention during the thesis to show their potential. The most useful methods based on the trials were thermal imagery in process monitoring and liquid tests for analysis for finished cups. The perceived usefulness of thermal imaging can be explained by the significant role that heat plays in the sealing processes. The ability to use it in combination with other analysis methods further expands its use cases.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUT Energiajärjestelmät

Konetekniikka

Juho Bonifer

Kartonkikuppien valmistusketjun seuranta- ja analysointimenetelmien kehittäminen

Konetekniikan diplomityö

2023

68 sivua, 43 kuvaa ja 6 taulukkoa

Tarkastajat: Apulaisprofessori (Tenure track) Ville Leminen, TkT ja Dosentti Panu Tanninen, TkT

Avainsanat: Kartonkikuppi, kertakäyttökuppi, kuppien valmistus, monitorointi, analysointi

Tämän diplomityön tavoitteena oli kehittää kartonkikuppien valmistusprosessin tutkimuksessa hyödynnettäviä seuranta- ja analyysimenetelmiä. Opinnäytetyö koostuu kartonkikuppien valmistusprosessia sekä moderneja kuppimateriaaleja ja -koneita käsittelevästä kirjallisuuskatsauksesta sekä tutkimusosasta, jossa kuppimateriaaleja koeajettiin seuranta- ja analyysimenetelmien testaamiseksi. Opinnäytetyössä keskityttiin pinnoitettuihin tilavuudeltaan 250 ml oleviin kartonkisiin kuumakuppeihin.

Opinnäytetyön tutkimusosassa kahdeksasta referenssimateriaalista ja kolmesta kokeellisesta materiaalista valmistettiin koeajoissa kartonkikuppeja. Koeajojen päätavoitteena oli löytää kullekin materiaalille toistettavat prosessiparametrit sekä testata eri seurantamenetelmien käyttökelpoisuutta ajojen aikana. Koeajoissa valmistettuja kuppeja taas käytettiin kuppien analysointimetodien testaamiseen. Lähes kaikille testatuille materiaaleille löytyi sopivat, toistettavat parametrit. Jotkut materiaalit kuitenkin kärsivät ajettavuusongelmista, jotka liittyivät mahdollisesti kitkaan, liialliseen lämpöön tai kahden jälkimmäisen yhteisvaikutukseen.

Löydetyt prosessiparametrit olivat loogisia ja kokeellisten materiaalien ajettavuus oli verrattavissa niiden kaupallisiin verrokkeihin. Suurin osa käytetyistä kuppianalyysimenetelmistä todettiin käyttökelpoisiksi, vaikka jotkut tuntuivatkin liiallisilta tai eivät saaneet tarpeeksi huomiota opinnäytetyön aikana osoittaakseen potentiaalinsa. Hyödyllisimmiksi menetelmiksi paljastuivat lämpökuvaus prosessin seurannassa sekä nestetestit valmiiden kuppien analysoinnissa. Lämpökuvauksen koettu hyöty selittyy lämmön merkittävällä roolilla osana valmistusprosessia ja kyvyllä yhdistää se muihin menetelmiin.

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Lappeenranta, 2.2.2023

Juho Bonifer

SYMBOLS AND ABBREVIATIONS

Abbreviations

CD	Cross direction
HDPE	High-density Polyethylene
LDPE	Low-density Polyethylene
MD	Machine direction
PE	Polyethylene
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoate
PHB	Polyhydroxybutyrate
PLA	Polylactic acid
PP	Polypropylene
SEM	Scanning electron microscopy
WBBC	Water based barrier coating

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1 Introduction

Disposable cups are an integral part of the modern takeaway culture. They must be able to contain hot, often slightly acidic liquids like coffee, which sets some requirements on the properties of the cup material. Plastic materials are traditionally used, as they are cheap, inert, easy to form into containers and have good barrier properties. As plastic waste is becoming a bigger problem every year, fiber-based alternatives like paperboard are starting to replace plastic as a material in packaging due to their recyclability. Fiber as a material, however, has poor barrier properties against fats and absorbs moisture when in contact with liquids or high-moisture products, facilitating a barrier coating to be applied to the paperboard (Rhim & Kim, 2009, Schouken et. al. 2014). The barrier materials have traditionally been low-density polyethylene, biobased polymers like PLA or natural wax.

Sustainable materials are continually researched to find an economical, green alternative to replace LDPE coating in packaging. In their article, Buxoo & Jeetah (2020) researched the possibility of using fibers derived from what was normally considered waste, to produce cups of satisfactory quality, even without synthetic binders. The materials can't release any harmful substances into the beverage, and in the case of hot beverage cups, they need to provide some insulation to protect the hands of the consumer. The research of water-based barrier coatings has also been active in the recent years, looking to be a promising alternative to PE-coated boards, since they can be biobased, recyclable, and even biodegradable.

According to TAPPI, the size of the global hot beverage paper cup market was already 116 billion units in 2018. When combined with cold beverage cups and cups for food items like noodles, 250 billion cups enter landfills globally every year. (TAPPI, 2019.) Even a fraction of this amount disposed improperly into the nature causes a noticeable amount of plastic pollution, making developments in the materials or recycling infrastructures necessary. As PE-coated paperboard is difficult or even impossible to recycle in conventional recycling mills due to the strong bond between the coating and paperboard, developing bio-based, compostable, or biodegradable materials has become an attractive alternative (Foteinis, 2020). Following the development of novel, sustainable materials the manufacturing processes and machinery need to match their needs; the general forming process is nearly identical to the one used when disposable cups first became popular. The thesis was done in cooperation with Stora Enso as part of a joint project with LUT University, providing the required materials and guidance during the thesis.

1.1 Goals of the thesis

The goal of this thesis is to gain a better understanding of how the manufacturing chain of paper cups is affected by the interaction of different, especially novel materials, process parameters and machine adjustments as well as use this knowledge to develop the monitoring and analysis methodology. A secondary goal of the thesis is to increase the consistency of cup forming by increasing the accuracy and documentability of adjustments.

1.2 Scope & limitations

The focus of the thesis will be on developing monitoring and analysis methods for understanding the interaction of material properties, machine adjustments and process parameters. The adjustments and parameters will be studied in a generalized fashion to avoid difficulty in applying the gathered data to other cup forming machines.

1.3 Methodology

The thesis consists of a literature review, practical tests and analysis of data acquired during them. The gathered data will be used to try and formulate a model to better monitor and adjust the process relative to the used materials.

1.4 Literature review

The literature review of this thesis will begin with introducing the cup manufacturing chain and its sub-processes along with their alternatives. After which the global state of the disposable cup forming market, including modern forming processes, machines, cup materials and their development prospects will be presented. The disposable cup industry desperately needs to reduce its consumption of fossil-based plastics, the most common of which will briefly be introduced along with biobased alternatives. Special attention is paid to water-based barrier coatings and their applicable coating methods, as it is a promising technology for applying biobased and/or biodegradable barrier technology. Additionally, cup quality factors in manufacturing are briefly discussed. Search words and phrases such as paperboard cup, paper cup, disposable cup combined with the desired area like market, forming etc. were mainly used to find information.

1.4.1 Paper cup forming process

Paper cups are formed in a multi-stage converting process from coated paperboard blanks, presented in Figure 1. Heat and pressure are used in combination with the barrier coated surfaces create liquid-proof seals without the need for additional adhesives.

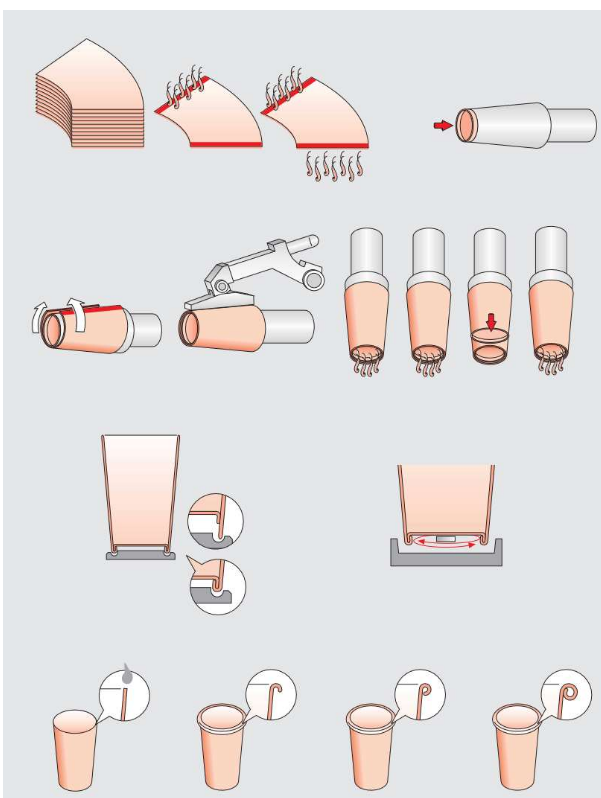


Figure 1. Stages of the paper cup forming process. (Hörauf. 2022).

The stages presented in the figure are as follow:

1. Blanks are fed and the side seam surfaces are heated
2. The bottom is punched and inserted into the bottom of a tapered, cup shaped mold (a mandrel)
3. The heated wall blank is wrapped around the mandrel and seamed
4. Bottom heating in one or more stages
5. The cup wall is curled to envelop the edges of the inserted bottom blank
6. The curled cup walls are pushed into the enveloped bottom blank by the knurling tool, creating the bottom seal
7. Application of mineral oil to the rim
8. Rim roll forming in (usually) two or more stages

In the side seaming stage, heat, pressure, and time are used to create a lap seam by wrapping the blank around a tapered cylinder, the mandrel, and applying pressure to the overlapping surfaces to form the walls of the cup. Since no glues are used in modern, single walled disposable cups, the seal is formed by bringing the polymer barrier coating on the seam surfaces of the blank to a molten state, usually by using hot air or flame. The heated surfaces are then pressed together and allowed to cool briefly, recrystallizing the polymers, and finishing the side seam. The molecular principle of this process is presented in Figure 2. When using single-side coated paperboard, the molten coating adheres to the uncoated fiber surface of the blank instead of bonding with the molten coating on the other side.

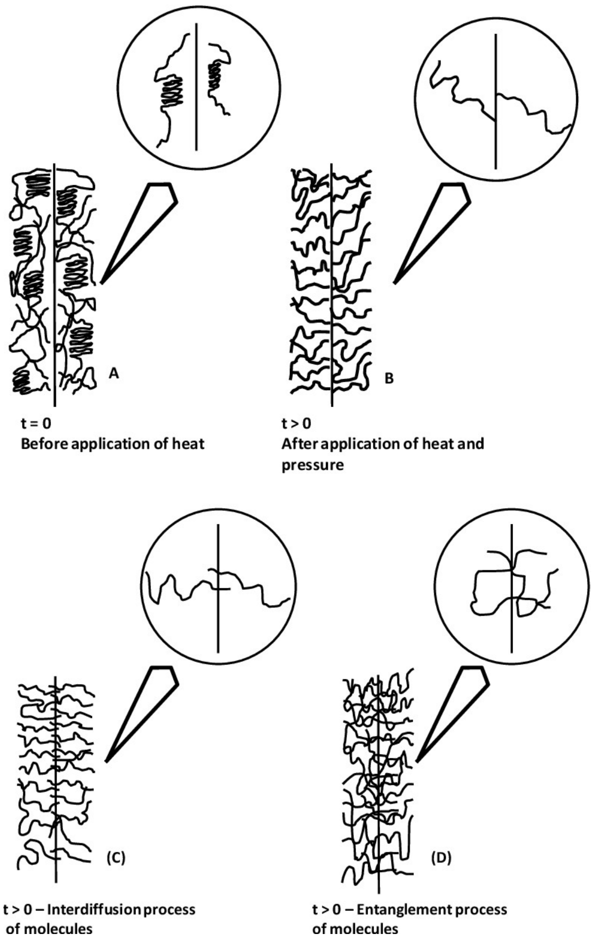


Figure 2. Molecular principle of heat sealing (Mihindukulasuriya, 2012)

Steps C and D in the previous figure are vital to the seal forming process and can be disrupted if incorrect parameters are used. As the side seal is being formed, bottom blanks are punched from a web of paperboard bottom stock and inserted into molds. As the previously seamed cup bodies arrive at the next station, they are pushed onto the molds with the bottom blanks inside, followed by bottom heating in preparation for bottom curling and knurling. Examples of the tools used for these stages are presented in Figure 3.

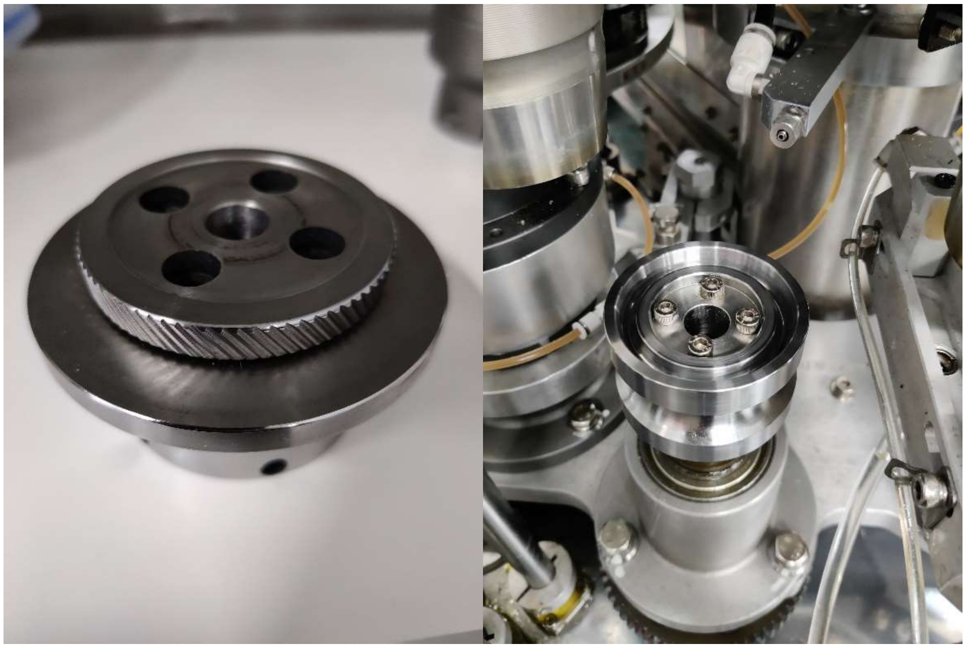


Figure 3. Left: Patterned knurling tool. Right: Curling station (LUT packaging laboratory)

Bottom curling is typically done with a spinning, concave tool that forces the heated parts of the cup walls into a curve around the inserted bottom blank (Figure 1). The knurling step uses a patterned disc, which spins and presses the heated and curled cup wall into the bottom blank it is enveloping, producing a watertight seal via the same principle as in side sealing.

The final stage of the manufacturing chain is rim roll forming. The purpose of the rim roll is to increase the rigidity of the cup, make the cup more enjoyable to use and to tuck away the raw edge of the paperboard, preventing the exposed layers from absorbing liquids. Rim roll forming happens in multiple stages: The rim of the cup body must be lubricated, usually with food grade silicone or mineral oil, to allow the rim to slide properly while being tucked. Especially in the rim forming of two-sided materials, both surfaces contacting each other are coated, which could cause friction problems without oil, depending on the barrier material. The lubricated rim is then pressed down by tapered tools into a roll shape, usually in at least two steps. The forming process is based on the controlled deformation of the paperboard, namely delamination. (Upadhya & Nygårds, 2017.)

As the stages of cup forming are performed successively from blanks all the way to finished cups, each stage affects the following ones as well. The most critical steps to ensure a functioning cup are the side seaming and bottom forming steps, while the most mechanically complicated step is rim roll forming.

Alternative sealing methods

Ultrasonic sealing, often called ultrasonic welding, is a popular method for forming side seams and can be used to compliment or to replace conventional hot air sealing. In ultrasonic sealing, the polymer coating is heated by applying acoustic vibrations to the seaming surface through the sonotrode during the pressing action instead of heating the surfaces prior to it. The amount of heat generated in the material is dependent on the amplitude and frequency of the vibrations as well as the active time of the sonotrode. (Charlie et. al. 2021.) Similar to hot air temperature, the active time needs to be adjusted according to the coating of the paperboard. This process generates localized heat inside the sealing surfaces, slightly reducing unwanted tool heat up, thus leading to a more consistent process.

Ultrasonic sealing also seems to be quite a sensitive method, as pointed out in an article by Charlier et. al. (2021) researching the ultrasonic welding of paper materials. The materials researched in the paper had a lower grammage of both paper and coating compared to cup materials, but it managed to highlight the importance of the correct seaming power and material thickness in fiber-based materials with low coating weight. Low material thicknesses especially seem to reduce the efficiency of the sealing process.

1.4.2 Cup quality

The quality of cups is evaluated by their functionality and performance, as well dimensional and aesthetic properties. The cup has to look pleasing to the eye, but functionality is still the most important factor. In addition to liquid-tight seals in the side and bottom seams, the cup must also be rigid enough as to not change its shape while being held. The used paperboard material affects the rigidity, but it may also be reduced by some forming defects. The rim roll of the cup must be properly formed, as a bad rim reduces the stiffness of the entire cup or cause liquid to leak onto the outer wall. A well-formed rim roll must look tight, be fully tucked, and have a round shape. Two well-formed rim rolls in addition to two defective ones are presented in Figure 4. (Upadhyaya & Nygårds, 2017.)

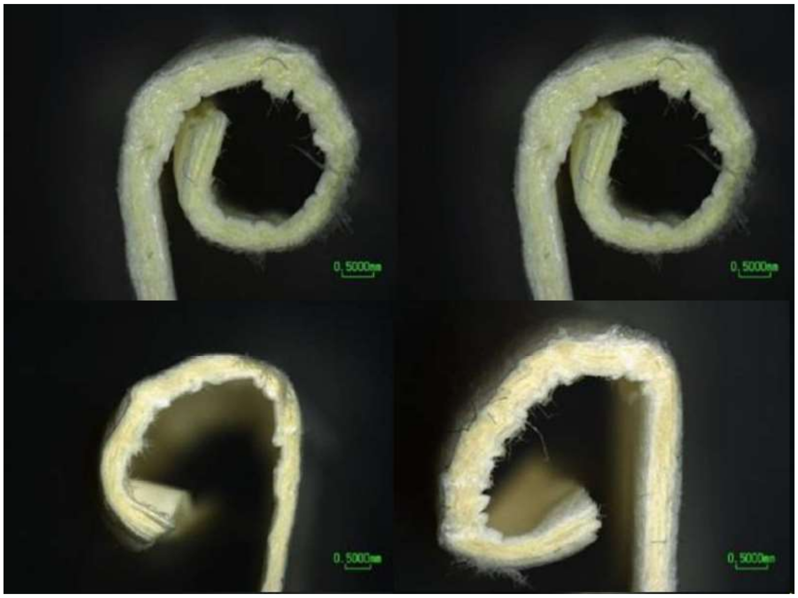


Figure 4. Cross-sections of well-formed rim rolls (1,2) and badly formed rim rolls (3,4) (Mod. Upadhyaya & Nygårds, 2017)

As seen in the figure, the well-formed rim rolls have an even circular shape and a slight bulge on the opposite side of the rim roll, which Nygårds & Upadhyaya (2017) state to be integral to properly formed rim rolls and is notably missing on the bad ones. The good rim rolls also have even delamination, while it has failed in the bad ones, causing a crease in the formerly mentioned bulge area.

1.4.3 Commercial disposable cup materials

A typical paperboard material used to manufacture disposable cups, often called cupstock, can be seen in Figure 5. It consists of a baseboard, which is made up of a combination of pulp layers, each with their specific purpose, and a polymer coating on the side in contact with the liquid or alternatively on both sides.

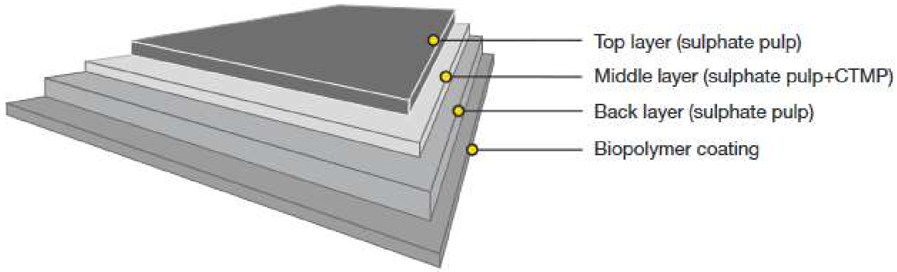


Figure 5. Structure of a biopolymer coated paperboard by Stora Enso (Stora Enso. 2021)

2-side coated paperboards can be used for cold beverage cups for example, to combat the penetration of condensed water on the outside of the cup into the fibers. Pigment coatings may also be applied to the outside ("over the Top layer" in Figure 5) of the paperboard to improve printability and print quality by providing an even surface (Paltakari, 2009). The pulp layers provide the required stiffness for the intended application while the polymer coating is responsible for seal adhesion and creating the barrier against oils and liquids, which is naturally weak in uncoated paperboard due to its porous structure (Alava & Niskanen, 2006).

With the push for more sustainable material options, commercial biobased and biodegradable or industrially compostable cup materials are gathering increasing interest. A study conducted in 2022 by Filho et. al., concluded that consumers have relatively good knowledge of bioplastics, but their daily use is limited by their availability or price. Bioplastic coatings are a promising alternative to conventional fossil-based polymers due to reaching similar properties while being made up of renewable materials, being biodegradable or both. All bioplastics are not biodegradable, and all biodegradable plastics are not biobased. For disposable cups, polymers that are both biobased and biodegradable would be preferred. A more in-depth breakdown of biopolymers is presented in Figure 6.

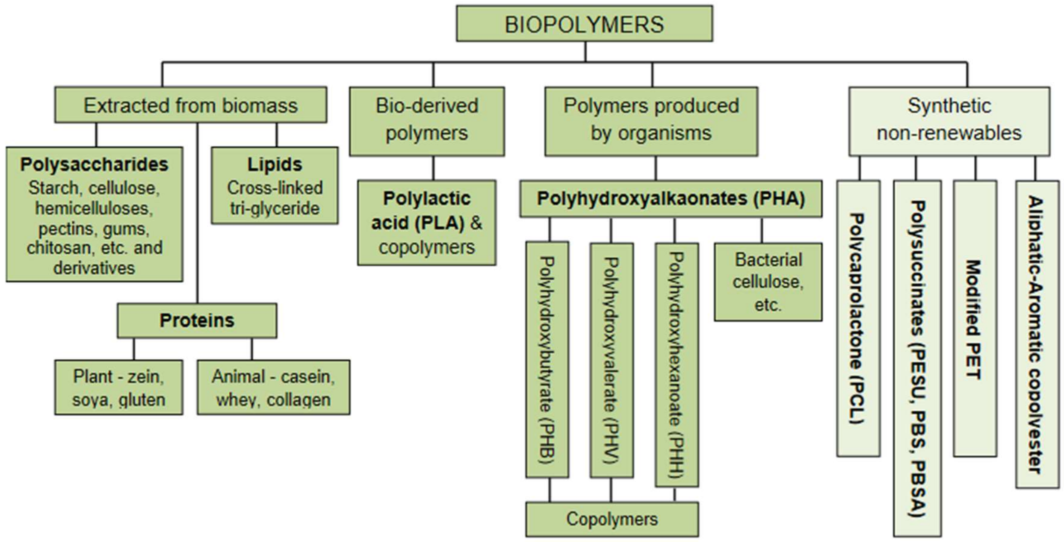


Figure 6. Classification of biopolymers by their source. (Vähä-Nissi et. al. 2011)

Bioplastics already commonly used for liquid barrier coatings include thermoplastic starch, polylactic acid (PLA), polyhydroxyalkanoate (PHA) and their blends. These polymer coatings and their blends are made from renewable materials and are compostable in industrial conditions, meaning process temperatures must reach over 50°C. PLA is a biopolymer produced through bacterial fermentation of carbohydrates and has barrier properties similar to PP and PET (Castro-Aguirre et. al. 2016). It can be farmed and produced from corn, for example, but faces the common problem of taking up area usable for food crops.

Some common problems with many biobased options, however, is their affinity for water and low flexibility of the formed barrier. Starch and PLA, for example, have 2.5-5 times higher water vapor permeability than the commonly used LDPE. Brittleness caused by their low flexibility can result in pinholes and cracks during converting and forming, which harms the container's intended barrier against liquids. (Tyagi et. al. 2021)

A type of PHA, polyhydroxybutyrate (PHB), is readily biodegradable, meaning it degrades even in colder conditions like sea water. PHB, as well as PLA can be applied via extrusion coating by using existing equipment, increasing their viability as a replacement for the fossil-based LDPE. Since a significant portion of disposable cups end up discarded or in landfills instead of being properly recycled, biodegradability is going to be an important factor until the recycling rates can be increased (TAPPI, 2019). The higher unit cost of bioplastics, however, is still the biggest single factor inhibiting the total replacement of fossil-based barrier materials.

Barrier coatings are applied to paperboard as either an on-line process as part of the production of paperboard, or off-line as a separate process. Off-line processes offer more controllability and less limitations than their on-line alternatives but have lower production capacity and higher investment costs (Kuusipalo et. al. 2008). Both are viable alternatives for applying extrusion coating and dispersion coating, which are commonly found in cupstock and food service boards.

Extrusion coating is a coating method in which a polymer with a high melting point, often LDPE, is extruded onto a web of paperboard in molten film form. It is perhaps the most commonly used process for applying both fossil-based and biobased coatings to paperboards. As the polymer is molten when applied, it creates a strong bond between the polymer layer and coated board, which causes problems with separation during recycling.

Besides bioplastics applied by extrusion or lamination, water-based barrier coatings (WBBC) and latex based coatings are a promising alternative to fossil-based LDPE. They are applied onto the paperboard by dispersion technology. The dispersion coating method is used to apply a water-based latex barrier coating to paperboard to create a barrier against liquid and oil. Latex coatings are composed of polymer particles dispersed in water alongside additives and fillers which improve barrier properties and runnability. A typical latex coating can contain 10-20 components in total. The suspended polymer particles are typically 50-300 nm in diameter. This dispersion is applied onto the paperboard and dried, which causes the polymer particles dispersed in the liquid to coalesce into a film. The principle of this technology is shown in Figure 7. The simplest dispersion coatings contain only synthetic polymers suspended in water, but the use of biopolymers, for example modified starch, in combination with synthetic ones has become more common through research. (Ovaska, 2016)

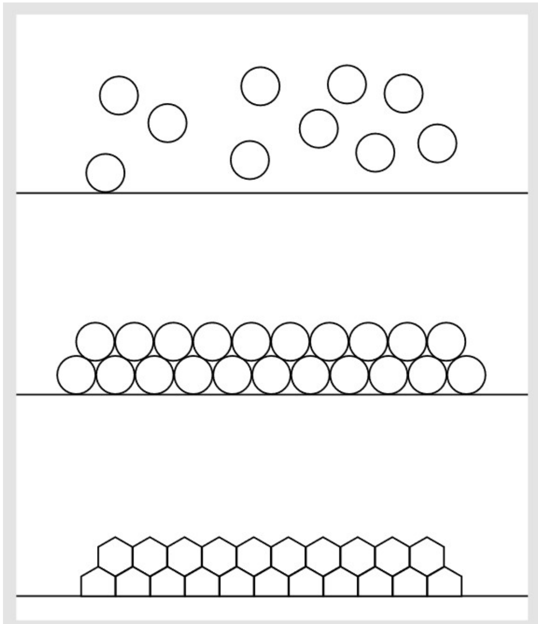


Figure 7. Principle of dispersion coating. (Kuusipalo 2008, 62.)

During application, dispersion coatings need to be metered and dried to ensure satisfactory barrier properties. In metering, the dispersion on the surface of the baseboard is distributed evenly and any excess is removed. The method used for metering directly affects the form of the coating surface: blade coaters give an even surface by removing excess dispersion while air knife coaters and curtain coaters give an even coating layer which follows the contoured surface of the baseboard. Rod and bar coaters apply a surface finish somewhere between an even surface and even coating.

While an even coating surface is better suited for printing, an even coating layer following the contours of the paperboard is typically preferred; an even surface causes the coating thickness to be thinner on the highest points of the surface contours, which can deteriorate its barrier properties (Kuusipalo. 2008). The difference in the surfaces can be seen in Figure 8, which also demonstrates the differences in coating thickness caused by contours in an even surface coating.

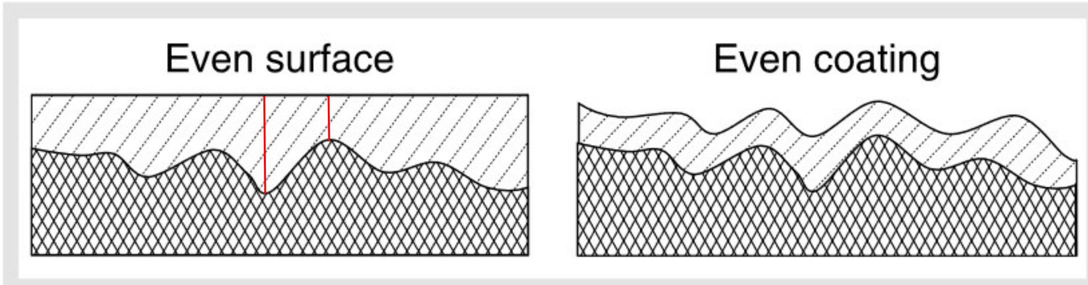


Figure 8. Comparison between even surface and even coating. Inconsistent coating thickness highlighted in red (even surface). (Mod. Kuusipalo. 2008)

The barrier properties and runnability of dispersion coated materials are comparable to those of commonly extruded materials like LDPE. Generally, water-based dispersion barriers have excellent barrier properties against oil and water, which can be further enhanced via additives. Kotka mills (Papercon, 2019) states that, in order to have good runnability for dispersion coated materials, the cup forming machines need to be well maintained and adjusted accordingly for each material caliper. However, due to the low thickness (5-15 µm) of dispersion coatings, they are susceptible to pinholes which may compromise the required barrier properties. (Kuusipalo, 2008)

Hygienic and safety factors are also vital when developing materials that come in contact with foodstuffs. The materials used in packaging must be sufficiently inert to not react with any foodstuffs they may contain. In the EU, regulation number 1935/2004 states that the materials can't transfer substances to food in quantities that could endanger human health, degrade the food, or change its composition (Eur-Lex, 2021). Another regulation concerning coated, disposable cups is regulation number 2020/1245 on plastics in contact with foodstuffs. In addition to the general guidelines set in the previous regulation, it contains more in-depth information such as specific migration limits of different substances (Eur-Lex, 2020).

1.4.4 Commercial cup forming machinery

Modern, industrial cup forming machinery can reach production speeds of up to 330 cups per minute and are able to form cups of different sizes by changing their toolset. They perform all steps of cup forming as a continuous operation, starting from pre-cut blanks and a bottom stock web with a ready-to-use cup as the end product. Some machines have an integrated die cutter which allows the wall blanks to be web-fed as well. Some of the biggest manufacturers of industrial scale paper cup machines are Hörauf from Germany, the paper machine company (PMC) from the U.S.A and Newtop from China.

Most commercial cup forming machines have a control system based on a programmable logic controller (PLC) using sensors and/or machine vision. The sensors can identify errors in production e.g., failure to remove the cups from molds or errors in feeding, while machine vision can identify defects and reject them based on predetermined parameters. Servo driven machines which enable the control of each process stage independently are also available but are more expensive and not as common as single-drive machines. The main manufacturer of servo-driven cup machines is Paper Machine Corporation.

The most common seam heating method for industrial machines is hot air, since it is easier to configure than ultrasonic side sealing and has a longer history in use. Ultrasonic sealing systems take up a lot of space inside the machines and may also suffer from faster production speeds because of the shortened activation time and holding window.

The most notable difference between commercial cup forming machines is their orientation of operation. The most common configurations are as follow:

- Cups travelling parallel to the revolver during side- and bottom sealing. The revolver can be horizontal or vertical. Figure 9 displays a vertical design by Hörauf.
- Cups travelling perpendicular to a vertical revolver during bottom forming stages, presented in Figure 10. In this design by Newtop, side seams are formed around a separate mandrel before entering the revolver’s molds

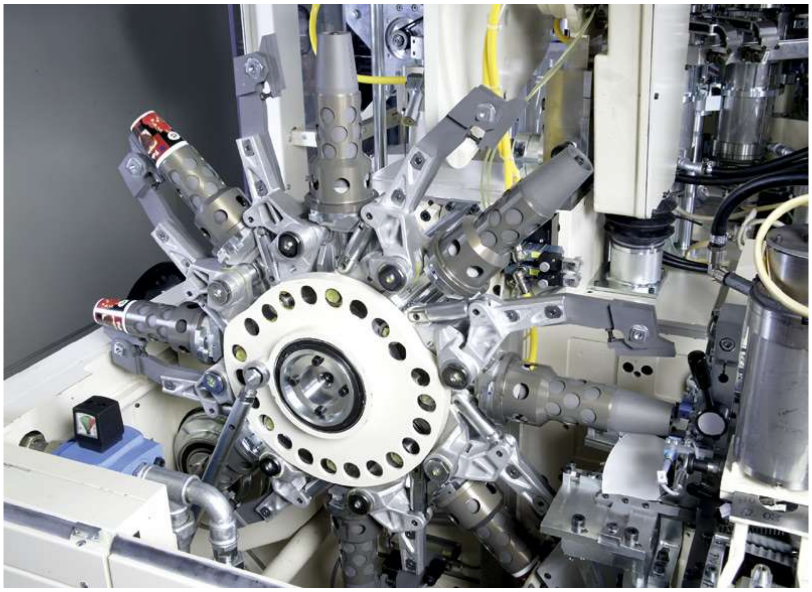


Figure 9. A Cup travelling parallel to the revolver in Hörauf's BMP series 200 cup machine. The seam holding clamps are located on each mold. A fed blank is also visible on the right. (Hörauf. 2022)

Figure 10. Cup travelling in a mold perpendicular to the horizontal revolver, situated between the bottom heaters. The side seams are cooled by fans before entering the bottom forming steps.

Most cup machines reaching production speeds above 200 cups per minute use some variation of the parallel configuration presented in the former of the two figures. These machines can have the side seam holding clamps be attached onto the revolver itself as seen in Figure 9, allowing the seam to be heated before entering the mandrels and then be held for the full time the cup is traveling on the revolver, preventing the seam from opening while still hot. Some machines can combine a vacuum system with the mandrels to hold the cup wall in place after a brief seaming action, essentially achieving the same hold time while using fewer mechanical clamps. Using ultrasonic sealing tools on parallel revolvers is hard if not impossible due to their design, however, as the ultrasonic stack requires a lot of space inside the machine compared to hot air. On perpendicular revolver systems, which ultrasonic sealing is commonly used with, the seam holding time is limited due to the seaming action taking place before the cup enters the molds of the revolver for bottom forming, limiting maximum production speed.

In addition to the industrial, state of the art cup forming machines, smaller home-business-scale machines are also available from smaller manufacturers. These machines are often semi-automatic instead of fully automatized and usually reach production speeds of 50-100 cups per minute instead of the 150-300 of industrial machines. Due to the slower production speed, ultrasonic sealing and the perpendicular revolver configuration are more common in smaller machines than in their industrial counterparts. Their prices are also noticeable lower, starting from 10.000 euros instead of the hundreds of thousands the industrial machines can reach, making them suitable for small-scale production. Most small-scale paper cup machine manufacturers are located in Asia, having China, India, and the Middle East as their main markets.

1.4.5 Development prospects

According to recent research and an increase in environmental awareness among consumers, bioplastics seem to be the best focus in development in addition to improving existing recycling infrastructure. While biodegradable materials reduce the amount of plastic that ends up in the environment caused by improper disposal, easily recyclable materials and a good infrastructure for recycling also facilitate the reuse of fibers. According to a lifecycle study conducted by Huhtamäki and Stora Enso (2019), recycling can reduce the carbon footprint of a single-use PE-coated disposable cup by up to 54%, increased to up to 64% if plant-based PE is used.

In addition to the coating on the inside of a disposable cup, plastic or polymers are found on the lids of takeaway cups. The same type of design challenge is present in developing the lids as in the cups themselves: They need to withstand heat and humidity of the hot beverages while maintaining a good mix of flexibility and rigidity when applied onto the cup to prevent spills, making the commonly used plastic a good material choice. Cup and lid material development should therefore complement each other. As with coated cups, the amount of plastic used for disposable lids isn’t insignificant either: According to the previously mentioned lifecycle study (Huhtamäki, 2019), the plastic in cup lids contribute more than 50% to the total environmental impact of take-away coffee cups.

Companies offering fiber-based materials or converted products like Huhtamäki, Stora Enso and Metsä board have started bringing their fiber-based lid materials and solutions to the market, which are claimed to be plastic-free and easily recyclable alongside paper cups. Examples of two different fiber-based cup lid types are presented in Figure 11.

Figure 11. Left: Bagasse based cup lid (Huhtamäki). Right: Paperboard based cup lid (Metsä group).

The materials used for the lids are dispersion coated, recyclable paperboard or molded natural fibers derived from wood and bagasse, which is a by-product of sugar production. (Packaging Europe, 2022).

Due to their better recyclability and possibility to utilize bio-based components, dispersion coated paperboards are a promising development in the liquid board market. According to Oberndorfer & Greenall, 30-50% of the synthetic latex and most if not all co-binders in dispersion pigment coating could be replaced by bio-based equivalents without negatively affecting the properties too much. In dispersion barriers, completely replacing the synthetic components with biobased ones is the end goal. As currently is, however, fully biobased dispersion barriers suffer from oxygen permeability and runnability limitations in the coating process.

Combining a biobased dispersion barrier with a thin, extruded layer of PE has also been researched as an alternative to extruded PE coatings by reducing the total grammage of plastic coating (Vartiainen et. al. 2016). The research in question investigated multilayer coating combinations including extruded high-density polyethylene (HDPE), LDPE, cellulose nanofibril dispersion coating and aluminum oxide coating. While combining a dispersion barrier with extruded PE improves the board’s properties like hydrophobicity over a dispersion-only coating, the issue of PE’s recycling difficulties remains.

2 Materials and methods

In this chapter, the practical arrangements and required materials will be presented alongside the cup machine's process parameter and machine adjustment possibilities for its different sub-processes. Eight of the studied materials are previously known reference materials, which will be used as a comparison for the experimental materials. Parameters used for the reference materials will therefore be used to find suitable ones for the experimental materials if possible. Later, the monitoring and analysis methods and equipment to be trialed will also be introduced.

2.1 Practical test arrangements

The practical tests of the thesis will be performed in the laboratory of packaging technology at Lappeenranta-Lahti University of Technology using provided equipment. Coated paperboard sheets will be converted into cup wall blanks by using a flatbed die cutter and formed into cups using a high-speed intelligent Debao NewTop 138s (New Debao Machinery, Zhejiang, China) cup forming machine. The machine has a maximum cup production speed of 140 cups per minute, while some industrial cup forming machines can reach speeds of up to 330 cups per minute (Paper machinery corp., 2014.). The machine also includes a set of ultrasonic sealing tools in addition to the traditionally used hot air tools. The paperboard materials required for the practical research will be produced and supplied by Stora Enso.

As the first stage of practical tests, trial runs will be completed by converting a set of reference materials into cups. The goal of the reference runs is to form defect-free, aesthetically pleasing cups from each reference material, and to document the process parameters and tool adjustments needed to meet this goal. The documented parameters and possible adjustments are then used as reference when selecting parameters for the experimental material trial runs.

2.1.1 Monitoring and analysis tools

Monitoring and analysis of the process will be carried out in multiple stages. During the forming process, a thermographic camera will be used to evaluate the performance of the heating and cooling tools of the machine. Since the machine can produce up to 140 cups per minute, the possibility of improper heating or cooling must be considered. The position of the adjustable tools, e.g., blank positioning, bottom forming, and rim (sometimes brim or mouth) roll stations will be documented as needed during the reference runs and used as guidance during the experimental trials. The quality of the cups will be monitored via dimensional measurements, aesthetical factors and liquid penetration testing via coffee, dyed ethanol, and iodine water.

The parts used to adjust the blank position in the cup machine will also be redesigned as part of the thesis. The design process will be done in Solidworks 2021 edition and documented in the third chapter of the thesis. The goal of the redesign is to improve the reliability and documentability of adjusting the position of the blank for future research.

2.2 Trial run materials

A total of 11 coated paperboard materials will be used to study the effects of material properties on the cup forming process. Of these 11 materials, 8 will be reference materials used in the first trial runs to find parameter and adjustment combinations for each material that yield a consistent cup quality. All materials are based on the same baseboard. The materials will be stored in a controlled environment of 50% relative humidity and 23 °C prior to running, as recommended by the manufacturer. The reference materials and their coatings are introduced in Table 1. In 1-sided coatings, the coating material is always on the inside of the cup (= backside of the material).

Table 1. Reference materials and their coating types

Material	Wall coating	Bottom coating
Trial run 1 1S PE 1	1-sided PE coating	1-sided PE coating
Trial run 2 Dispersion 1S	1-sided dispersion coating	2-sided dispersion coating
Trial run 3 Dispersion 2S	2-sided dispersion coating	2-sided dispersion coating
Trial run 4 1S Bio	1-sided biopolymer coating	1-sided biopolymer coating
Trial run 5 2S Bio	2-sided biopolymer coating	2-sided biopolymer coating
Trial run 6 1S PE 2	1-sided, light PE coating	1-sided PE coating
Trial run 7 1S PE +outside pigment	1-sided PE coating, pigment coated outside	1-sided PE coating
Trial run 8 1S PP	1-sided PP coating	1-sided PP coating

In addition to the reference materials, 3 experimental materials with novel coatings will be tested. The performance of the experimental materials in the forming process will be compared to the reference materials in terms of cup quality, used parameters and any mechanical adjustments, if needed, to produce cups defect-free cups. Unlike the reference materials, which will only be run with the corresponding combination of wall and bottom material, two of the three experimental wall materials will be tested with each other's bottom material. The experimental materials are introduced in Table 2.

Table 2. Trialed experimental materials

Material	Wall coating	Bottom coating
Experimental PE 1 (reference)	1-sided PE coating	1-sided PE coating
Experimental PE 2	PE coating with additive	1-sided PE coating with additive
Experimental PE 3	PE coating with additive	1-sided PE coating with additive

2.3 Process parameters and adjustments

The reference material trial runs were used to find adjustments and parameters which resulted in cups of intended dimensions with each material, facilitating the documentation of adjustments, were needed for the experimental materials. Adjustment possibilities of the used cup machine's tools and process parameters are introduced and their importance and effect on the process will be explained.

2.3.1 Side seam sealing

For side seam sealing, two methods will be utilized for the reference runs, the first of which is hot air sealing, in which the sealing surfaces are heated by hot air before closing the seam by applying pressure to it. Used temperature settings varied depending on the material and machine speed from 200 °C to 450 °C, the latter being the maximum setting for the used machine. The second utilized method is ultrasonic sealing, which instead adjusting the temperature, is controlled by the active duration of the ultrasonic sealing tool. The correct active duration can vary from 0.05 seconds to 0.20 seconds, depending on the seal material. The upper limit of the activation time is limited by machine speed on the fastest setting, as the sealing tool would only be pressing down on the blank for roughly 0.20 seconds at a machine speed of 140 cups per minute. By reducing the machine speed, more active time can be used: At 80 cups per minute, which was the slowest speed used for the test runs, the dwell time increased to 0.324 seconds. The dwell times were calculated by viewing high-speed video material of the process, filmed via a Flir A8580 MWIR (FLIR, Wilsonville, USA) thermal camera, and counting the frames for which the tool was in the bottom position, as the duration of each frame was known.

In addition to process parameters, some mechanical adjustments also affect the sealing of the side seam. The placement of the blank on the hot air jets prior to sealing is controlled by a set of adjustable fingers that push the blank forward. A similar set of push fingers which move the blank to the heaters to the sealing station can be seen in Figure 12, on the right side of the blank.

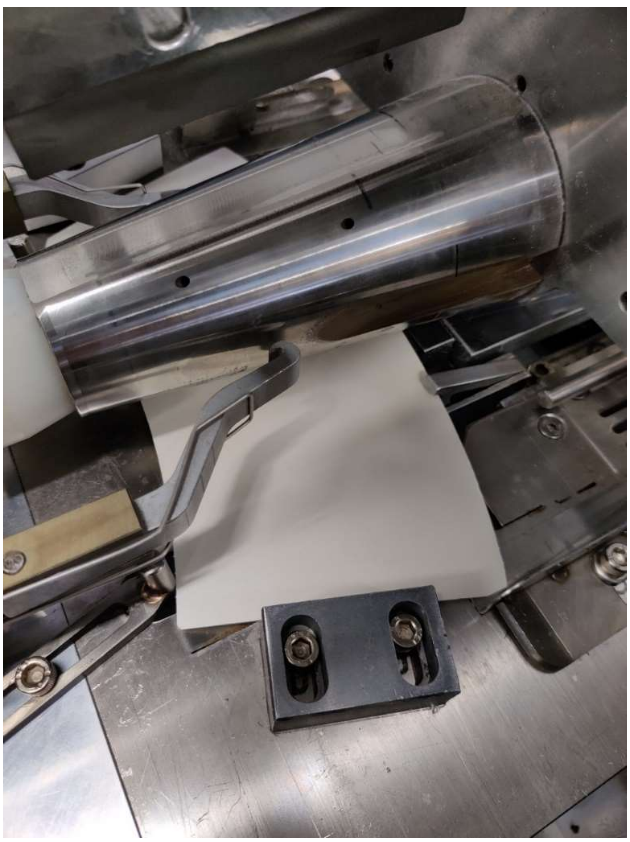


Figure 12. Blank positioning tools used for side seam sealing.

The rectangular guide pieces and stopper pegs also visible in the figure are responsible for stopping the blank in the correct position relative to the mandrel. They have identical counterparts on the other side of the mandrel and can all be adjusted independently. Moving the stopping position of the blank up on the mandrel increases its radius and reduces side seam width, while moving the position down has the opposite effects. Adjusting the position sideways affects the overlapping of the seam surfaces and can be used to correct a bad seal alignment or aesthetical errors but is not as critical as the positioning in the process direction.

2.3.2 Bottom forming

The bottom forming stage can be controlled by adjusting the bottom heating temperature and the height of the bottom curling and knurling tools. The force of the knurling tool is also adjustable. Before the curling and knurling tools, the cup bottom (inside the molds) and bottom part of the cup body are briefly inserted into stations heated by hot air in preparation for the bottom forming steps. The area of the cup wall affected by the bottom heating stations can be controlled by adjusting the station’s height. The heating stations are presented in Figure 13 and marked with (1) and (2) according to the process direction.

Figure 13. Bottom heating stations. The direction of rotation is marked with a red arrow.

The temperature of each heating station can be controlled separately but will be kept at a common temperature through the test runs to limit the number of variables. The height of the curling tool can be adjusted with a nut to control the amount of paperboard material used for the knurling stage. If the station is adjusted to be too high, the reheated side seam may partially melt and be forced open by in-plane stresses caused by the curling action, resulting in wrinkling or even an incomplete seal in the side seam near the bottom. This effect is increased if high sealing temperatures are used, since the polymers in the sealing surfaces don't have adequate time to cool down again and recrystallize.

The knurling station can be adjusted in two ways: height and knurling force. The correct height is dependent on the curling stage, as the knurling tool needs to reach and seal all the curled material to the bottom blank. Knurling force affects the strength with which the bottom seal is formed and should be adjusted in a way that produces liquid-tight seals but won't make the knurling pattern pronounced on the outside of the bottom flange. Too high of a knurling force can also damage the cup material, compromising seal properties.

2.3.3 Rim roll forming

The rim roll forming step is done in two stages, both of which can be adjusted in terms of height, controlling the amount of material forced into the rim tool. As rim forming is the last step of the cup manufacturing chain, it can and has to be adjusted according to cup dimensions dictated by previous stages. The success of the rim rolling stage is also heavily affected by material properties: low moisture content often causes the rim to rupture, and a high friction factor of the coating may prevent a good tuck. Rim forming tools require adjustments relatively rarely, as proper adjustments in the former stages tend to lead to a good rim roll.

2.4 Monitoring and analysis methods

Multiple monitoring and analysis tools were trialed during cup manufacturing related to the thesis. Some of the methods were previously known and planned at the beginning, while some were added later due to complementing another method or improvised based on previously used methods. In this section, the monitoring and analysis methods and tools used and trialed during the project are introduced.

2.4.1 Monitoring of thermal factors

As heat is a necessary component in forming seals in cups, thermal monitoring is an obvious way of acquiring information and evaluating the performance of the process. One method of applying thermal monitoring to the manufacturing chain is using a thermal camera to track the heating tools and heated blanks during seal forming. A Flir A8580 MWIR (FLIR, Wilsonville, USA) thermal camera was used to capture thermal footage of the process. The thermal footage can be used to evaluate the temperature of the cups/blanks in relation to the used parameters and to improve tool adjustments during the forming stages. The benefit of thermal imagery is limited in observing ultrasonic sealing, however, as the ultrasonic vibrations heat the seam surfaces from the inside during the dwell time of the sonotrode, making it impossible to track actual sealing temperatures. An example of thermal camera footage is presented in Figure 14, which shows the temperature of cup bottoms during the knurling step.

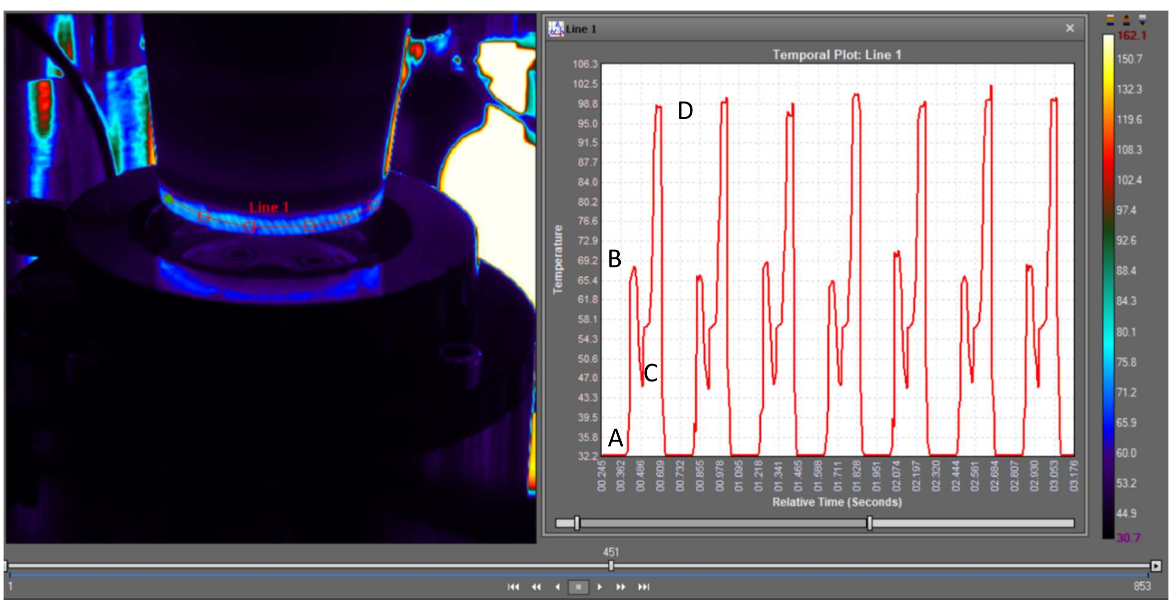


Figure 14. Temperature of cup bottoms during knurling (Approximate temperatures: A: 32 °C, B: 69 °C, C: 45 °C, D: 99 °C).

The peaks reaching about 100°C represent the temperature of cup bottoms before the knurling step, while the lower peaks reaching about 70°C represent the temperature after the knurling step was completed. In addition to the knurling step, the temperatures of the curling and side seaming stages will be monitored. The recorded temperatures should be regarded as comparative values inside their respective datasets because of possible differences in camera setup, ambient temperature as well as possible distortion from reflective surfaces.

Tracking specific filmed blanks is also a point of interest to compare reached temperatures to other blanks if any defects, material specific or otherwise interesting behaviors are noticed. The problem with thermal imagery is, however, that the readings are not actual values and instead should be used as comparisons. A marking method with low interference to the process, meaning minimal change to material thickness, friction properties and overall processability was tested in the form of a silver marker traditionally used for arts and crafts.

2.4.2 Analysis methods of formed cups and materials

The formed cups will be analyzed based on 3 factors: Functional, dimensional, and aesthetical. Dimensional accuracy will be evaluated by measuring the cup diameter, side seam width, rim roll diameter as well as bottom depth and diameter and compare them to dimensions determined by the machine tools. Functionality will be evaluated via a coffee test in which hot coffee is poured into cups and let sit for at least 10 minutes. The cups will periodically be visually inspected for leaks and pinholes. Leaks will result in liquid leaking through the seams, while pinholes manifest themselves as small holes in the coating surface, allowing liquid to reach the fiber surface. If none are detected, the cup passes the test. The test will reveal any defects or damage caused in the side seaming and bottom forming steps. Coffee is used because of its lipid content, which makes it more demanding on the paperboard than water and because of its prevalence as a takeaway drink.

Dyed ethanol is another common liquid used for testing finished cups. It is especially useful when looking for pinholes, as holes in the barrier coating allow the ethanol to penetrate into the baseboard, dying the fibers in the process. Even though ethanol penetrates the paperboard (especially the raw edges) much more easily than coffee even in well-formed cups, it can be used to analyze any damage done to the cup bottom via comparison between different temperature points and mechanical adjustments. In addition to finished cups, dyed ethanol will be used to investigate the effects of heat on pinhole forming by removing the blanks from the process after bottom heating, before applying any mechanical stresses to the bottom. Since bottom heating is directly followed by curling and knurling, which by themselves cause damage to the wall material as seen in Figure 15, enabling the isolation of process temperature as a variable.

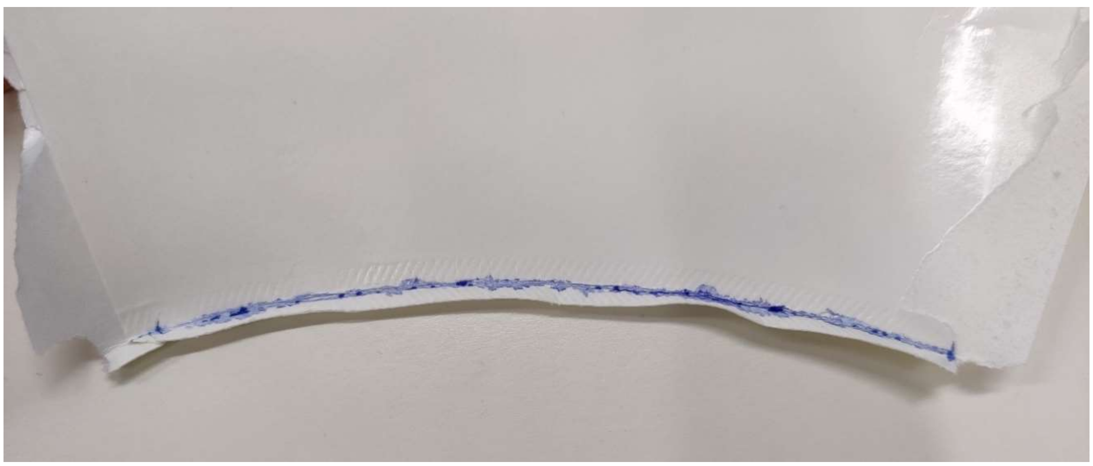


Figure 15. Mechanical damage (cracking of the barrier surface) caused by the curling and knurling tools revealed by dyed ethanol. Unheated sample.

The side seams of the formed cups were evaluated by tearing the seam open and assessing the portion of fiber tear to determine the mode of failure. A good seal should tear by separating the fiber layers of the paperboard from each other, while a bad seal tears by separating the coating surface from the fibers of the paperboard. The tear can further be analyzed by applying colored soap water on the tear surface. The colored water is then absorbed by the fiber surface, displaying the portion of fiber tear.

The possible uses of scanning electron microscopy (SEM) were trialed as a way of finding defects or causes to material behavior or to complement another monitoring or analysis tool. Scanning electron microscopes use a stream of electrons to scan a surface, which it then translates to images. SEMs are commonly used for viewing paperboard materials, but imaging parts of manufactured cups specifically has little information on it. Expected findings could include pinholes, damage caused by thermal and mechanical processes, e.g., knurling or heating. The final trialed analysis method was a magnetic thickness measurement device, which was used to evaluate the consistency and amount of sealing pressure.

3 Results and discussion

In this chapter, the results gathered during the reference and experimental runs via the monitoring and analysis methods introduced in the previous chapter are presented with the help of figures and tables.

3.1 Test run results and sealing ranges

In this section, the results of the test runs are presented, and for clarity, the materials will be classified by their coating types. Paperboards with similar coatings were compared to each other, after which a general comparison among all materials will be conducted to find correlations between process parameters and material behavior during the process. Sealing temperature ranges which resulted in a full fiber tear seal will be presented for both the bottom seam and side seams. The sealing ranges for side seams will also include ultrasonic activation times.

The cups were run as short series of 3-6 cups, usually starting at low process temperatures until the first appropriate sealing temperature was found, after which the number of produced cups was increased until a temperature resulting in a full-fiber tear without runnability issues or leaks was found. In short, the process is based on trial and error and knowing how the process interacts with the resulting cups.

3.1.1 Reference material runs

In all of the reference material runs, corresponding wall and bottom materials were used. The PE-coated cups all used the same bottom material. During the reference runs, all but two materials produced defect-free cups within the set tolerances at the maximum forming speed of 140 cups per minute. The materials in question are both coated with a dispersion barrier. The side sealing ranges for the reference materials are presented in Figure 17. The sealing ranges are process temperature ranges for the hot air heaters in which the materials in question have reached a full fiber tear in seals when torn. A comparison of dyed partial and full fiber tears is presented in Figure 16.

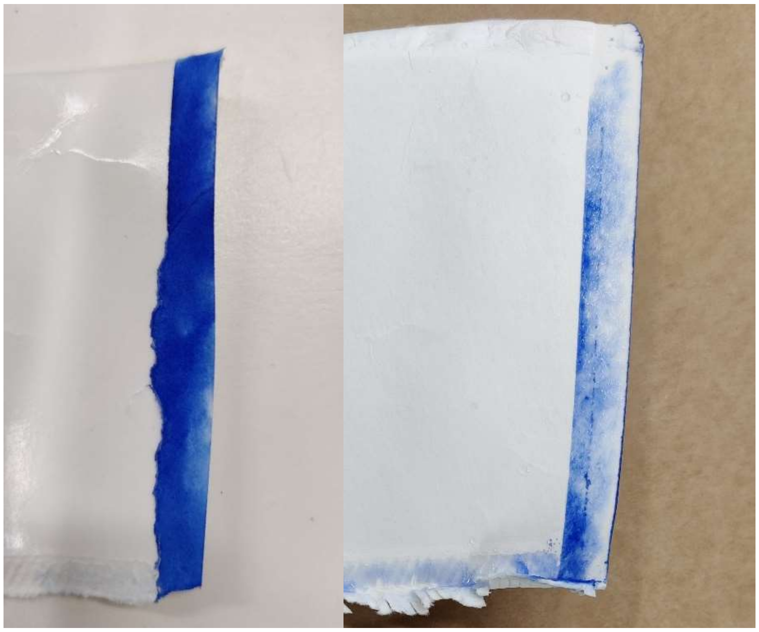


Figure 16. Left: Full fiber tear. Right: Partial fiber tear. Both surfaces were dyed using a water-dye solution.

A full fiber tear is characterized by the seam failing by the fiber layers of the material instead of the seal. In partial fiber tears the seal surfaces are separated from each other, which can be seen in the samples as white areas due to the barrier not absorbing the dyed water.

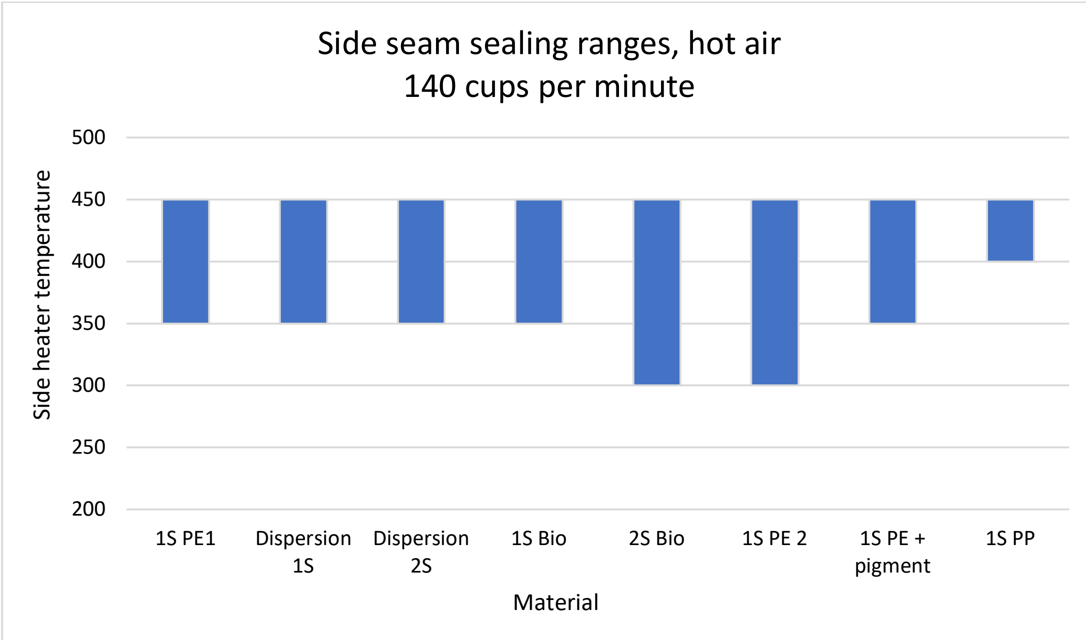


Figure 17. Sealing temperature ranges which resulted in a full fiber tear, excluding the two dispersion materials, which only reached a partial fiber tear at the available process parameters.

As seen in the figure, most materials are runnable at similar process temperatures except for the polypropylene (PP) coated cup, which is expected, as PP has a higher melting point than other commonly used barrier polymers. In addition to side seaming temperatures, process temperatures for bottom forming were also tracked. The temperature ranges for bottom forming presented in Figure 18 apply to both bottom heating stations as the temperature was kept equal between the two. The station temperatures were capped at 700 degrees instead of the maximum of 450 in the side seams.

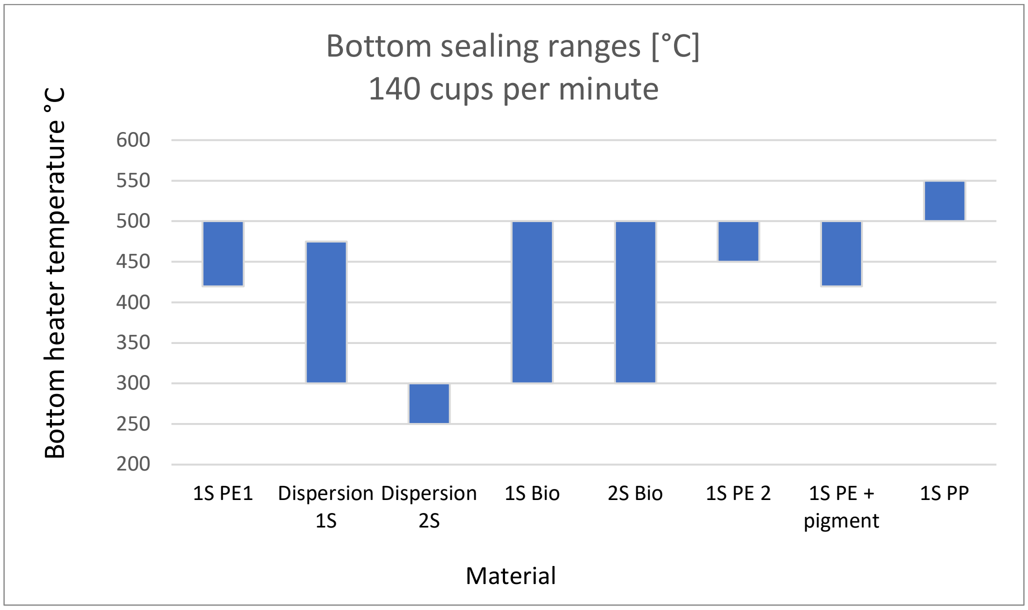


Figure 18. Sealing temperature ranges used to reach a full fiber tear in the cup bottom, excluding 2S dispersion, which only reached a partial fiber tear.

The bottom sealing ranges are similar to the ones found in the side seams. Differences can be found, however, most likely due to the increased maximum temperature that could be used. The bottom seal area typically started scorching at 500-550°C regardless of the material, limiting the sealing temperature below the machine maximum. Scorching should be avoided as it compromises the cup's sealing properties.

Ultrasonic sealing was tested in activation time ranges of 0.05 to 0.20 seconds at a production speed of 140 cups per minute. For all materials, the optimal sealing time was found in between 0.10 and 0.20 seconds. The activation time ranges for the reference materials can be found in Figure 19.

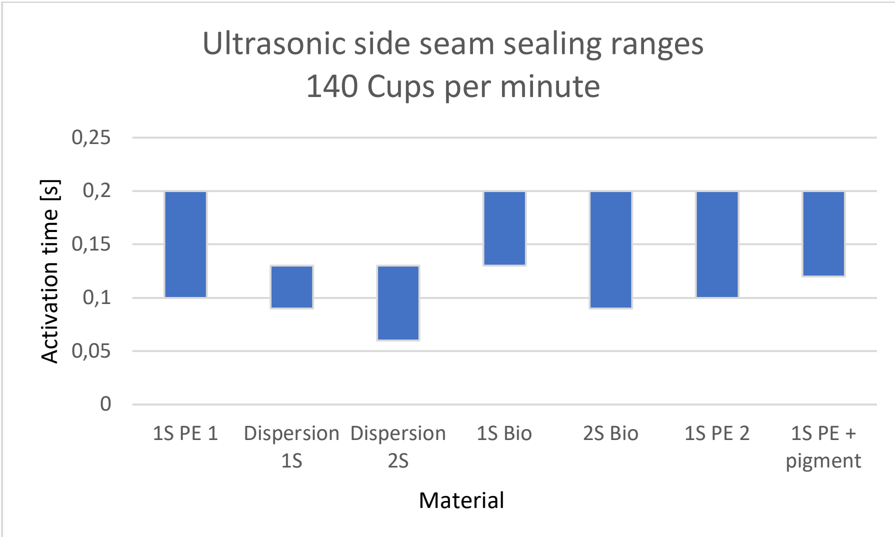


Figure 19. Ultrasonic activation time ranges used to reach a full fiber tear in the side seam, excluding the two-sided dispersion material, which only reached a fiber tear.

The side seams of PP-coated cups could not be sealed effectively by the ultrasonic sealer at the maximum process speed of 140 cups per minute, mostly producing cups without a proper seal. The most likely cause for this is PP's higher melting point compared to other common barrier polymers. The short window of ~ 0.20s for both the ultrasonic activation time and recrystallization at maximum speed doesn't leave adequate time for the sealing surfaces to bond together, causing the seal to open. On the other hand, lengthening the recrystallization period by lowering the activation time causes insufficient heat production to properly melt the polymer.

As seen in the previous figures, most materials could be sealed at similar temperatures and activation times, with the 1- and 2-sided biobased plastic coatings having the broadest sealing range. The ultrasonic activation times required by the PE-coated materials were relatively high compared to the process temperatures for hot air sealing, indicating a possible adjustment error in the ultrasonic runs.

3.2 Experimental material runs

The experimental material trial runs included three wall materials and three corresponding bottom materials. Each wall material was run with the corresponding bottom material with experimental materials 1 and 3 also being run with exchanged bottom materials and vice versa, to evaluate any effects this may have on bottom quality. Experimental runs were completed exclusively by using hot air sealing as the side sealing method of choice to limit the number of variables and avoid the adjustments ultrasonic sealing often requires during the test runs. Each combination of experimental materials could be formed into defect-free cups within the set tolerances at the maximum forming speed of 140 cups per minute. The dimensions were verified via calipers. An example of a cup produced from the experimental materials can be seen in Figure 20.

Figure 20. A cup formed from experimental material 3. The dimensions are within the set tolerances and the cup has no visible defects

The main goals of testing the runnability of experimental materials were to find viable process parameters for cup production and any major differences in runnability compared to commonly used materials. The side sealing temperature ranges which resulted in full fiber tears for each wall material are presented in Figure 21. The bottom sealing ranges are presented for each corresponding material combination as well as mixed combinations for experimental materials 1 and 3, since unlike in side sealing, both the wall and bottom materials have an influence on the seal quality.

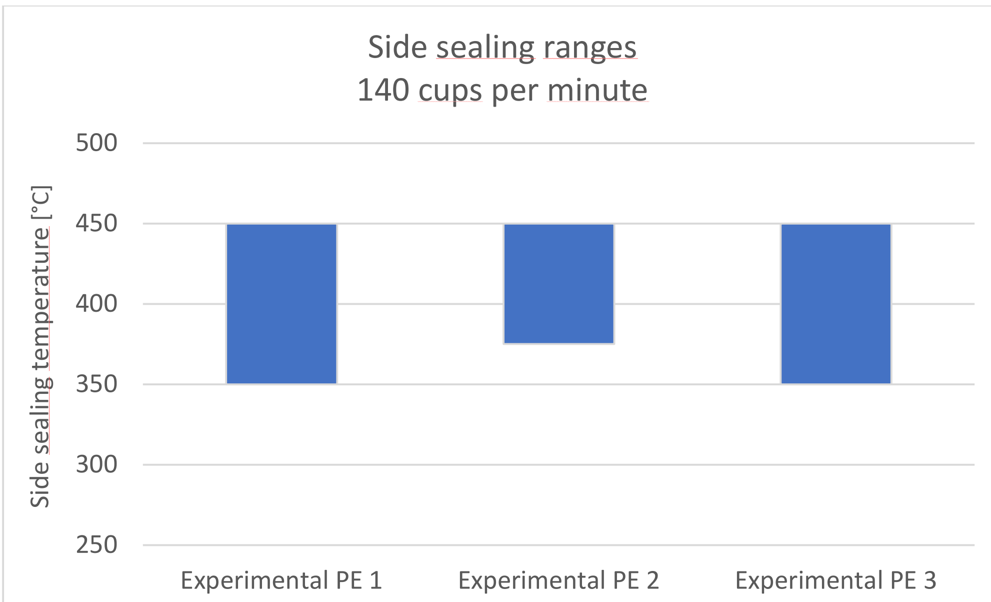


Figure 21. Side seam sealing ranges to reach full fiber tear in experimental materials 1,2 and 3

As seen in the figure, experimental materials 1 and 3 had a slightly wider sealing temperature range of 350 ℃ to 450 ℃ compared to experimental material 2, which could be explained by the material's slightly higher grammage of polymer coating (~8% difference). The achieved sealing ranges and seal quality are comparable to PE-coated boards, as can be seen in Figure 17 of the reference runs.

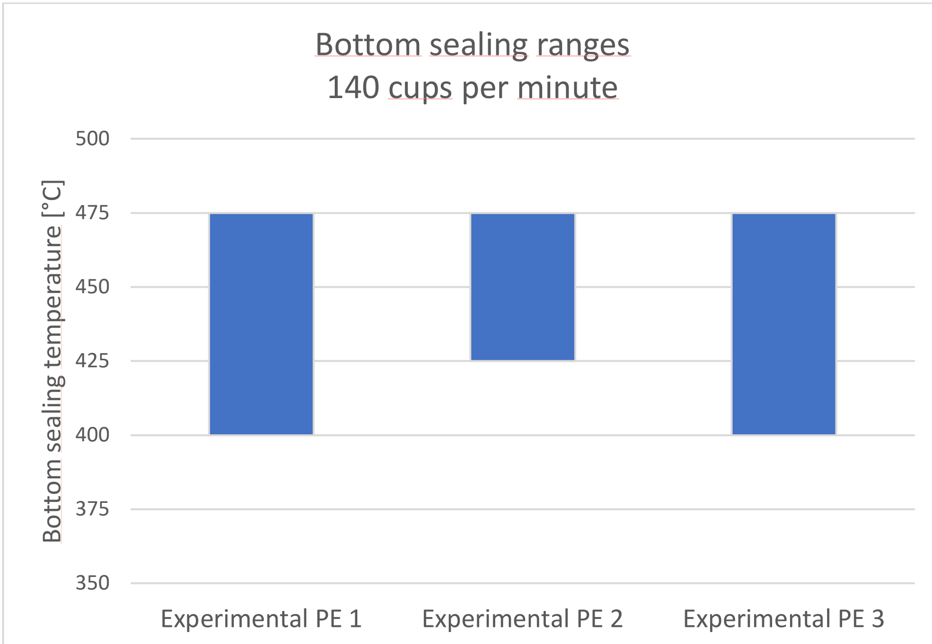


Figure 22. Bottom sealing ranges to reach full fiber tear in experimental materials 1, 2 and 3

The bottom sealing performance of the experimental materials was overall good and didn't require any mechanical adjustments. Experimental material 2 behaved in a similar manner as in side sealing, requiring a slightly higher process temperature for a full-fiber tear compared to materials 1 and 3. The lowest sealing temperature was 50 ℃ higher than PE1 reference material, which is the closest correspondent to a traditional PE-coating. The upper limit was the same at 475 ℃, however, as the cups began to leak in coffee tests at sealing temperatures of 500 ℃. The sealing performance of the mixed wall and bottom material cups was identical to the corresponding combinations, which is logical based on the original sealing results.

3.2.1 Coffee tests

To find the upper limit of bottom forming temperatures, hot coffee tests were conducted on the formed cups. All experimental materials had equal performance at each temperature point, passing the tests even at low temperatures which didn't cause a full fiber tear in the bottom. The mode of failure was also similar with all materials: High temperatures caused the coffee to leak at the site of the side seam, while low temperature caused the leaks to begin from random points of the bottom, which is presented in a comparison in Figure 23.

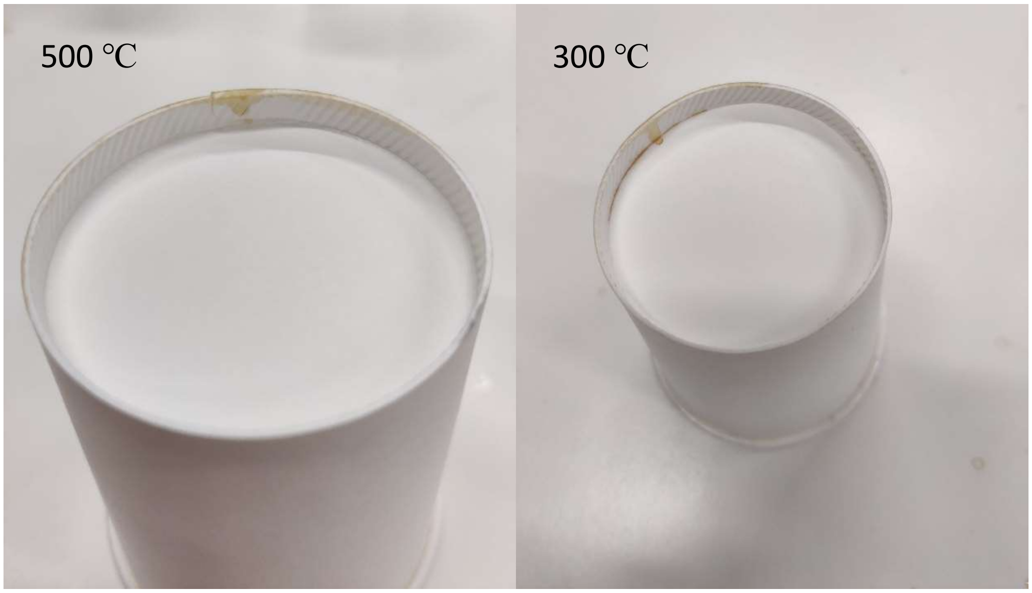


Figure 23. Comparison of failures in high and low bottom forming temperatures displayed by the hot coffee test. Experimental material 3.

The high-temperature failures are likely caused by the added thickness of the side seam in the knurled bottom flange, which causes it to sit closest to the bottom heaters and become damaged first by the heat. This can also be seen in bottom seals formed in high temperature, as the darkest part of the scorched area is most often located in the overlap of the side seam.

3.2.2 Pinhole analysis

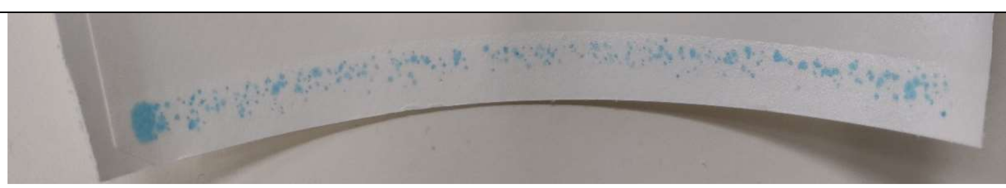
To try to find a relation between process temperatures and the formation of pinholes, the bottom heating of blanks was investigated, as it uses higher temperatures than side seaming and is in a bigger risk of leaks in use. Dyed ethanol was used to detect any pinholes. During testing, the bottom forming tools became problematic as they caused mechanical damage to the blanks even when unheated, and they directly follow the bottom heaters in the process.

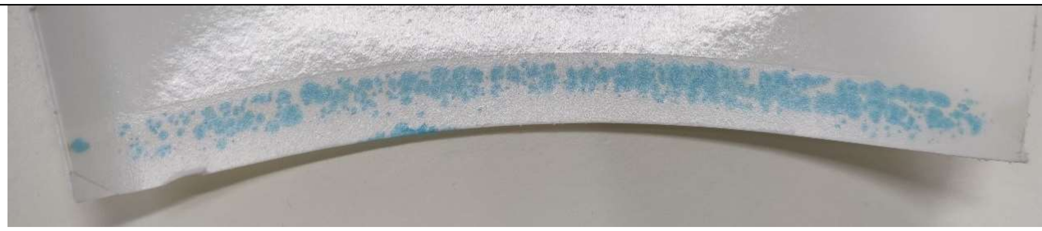
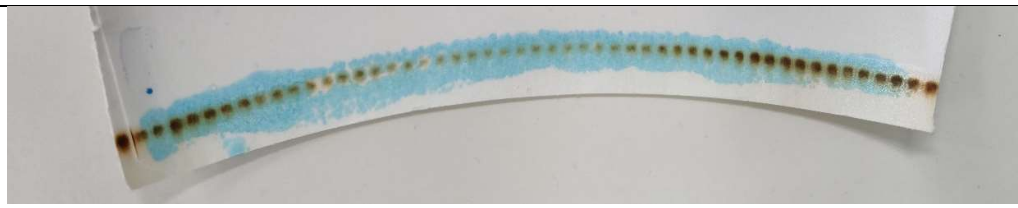
The blanks were therefore removed from the process after bottom heating to avoid any mechanical damage to the material.

Due to the gradual slowdown of the machine when stopping, the bottoms linger in the heaters for a longer time than in normal production, causing the temperatures presented to not be comparable to actual process temperatures. The number and severity of pinholes for each compared material was evaluated on a scale from 0 to 5 as follows and examples for each are presented in Table 3:

- 0: No pinholes
- 1: Few pinholes along the heated surface
- 2: Formation of some individual pinholes
- 3: Even spread of pinholes along seaming surface, dye marks start merging
- 4: Most of the heated surface is covered in pinholes, brown discoloration because of scorching
- 5: Large number of pinholes, blackened scorch marks

Table 3. Comparison of differently evaluated blanks

Eval.	
1	
2	

3	
4	
5	

The samples show a clear increase in pinholes as the process temperature is increased. The first samples show barely any pinholes while the heat affected zone is clearly visible. The highest temperature points on the other hand are completely covered in scorch marks and the ethanol has completely penetrated the heated surface. The blank displayed as severity level 5 would fail a coffee test without a doubt. In Table 4, a comparison between the pinhole findings of the experimental materials as well as the original reference, 1S PE 1 will be presented.

Table 4. Results of the pinhole evaluation

		Forming temperature [℃]				
		300	350	400	450	
Material	1S PE 1	2	3	3/4	5	Evaluation
	Experimental PE1	1	2	3	4	
	Experimental PE2	1	2	3	4	
	Experimental PE3	1	2	3	4	

The performance of the materials was good and complies with the results of bottom forming. The pinhole severity level 4, which was found at 400 °C in 1S PE 1 and at 450 °C in the experimental materials corresponds to a level of scorching that would be found in cups that have a chance of failing a coffee test. The difference in performance between the PE-coated reference materials and experimental materials could be explained by the slightly higher grammage of PE in the experimental coatings.

As PE-coated cups typically started failing in coffee tests at roughly 450-475 °C depending on coating grammage, an effective increase of ~75-100 °C in bottom heat transfer could be estimated for future tests due to the machine slow-down but should be verified via thermal camera. The completely black scorch marks of severity 5, found on 1S PE 1 would therefore correspond to a process temperature of 500-525 °C, which is over the documented maximum for the material and would result in a defective bottom. The analysis method looks to have use cases in research, given the linear results and the growing interest in researching dispersion coated materials, which are notoriously weak to pinholes. The results did have some inconsistencies inside series though, but it is unclear if they were caused by variations in the experimental material web, stopping the machine at slightly different times or variations in hot air temperature. These problems could at least partially be solved by temporarily removing or adjusting the bottom forming tools if deemed necessary.

3.3 Cup forming defects

Improper process parameter and mechanical adjustment combinations may result in defects during cup forming. Defects in the cups can negatively affect their aesthetic properties, usability, or both. The most common and severe defects encountered during the test runs, in terms of both usability and aesthetics will be presented by figures and their most probable causes will be explained.

An incomplete side seam seal near the rim roll is presented in Figure 24. This defect is critical since it can compromise the cup’s ability to hold liquid. This defect can usually be detected through an incomplete rim roll at the side seam as seen in Figure 25.

Figure 24. Incomplete side seam, two-side dispersion coated paperboard.

Figure 25. Opened rim roll caused by incomplete side seam. Two-side dispersion coated paperboard

Opening of the rim roll is caused by the materials at the top part of the side seam not adhering properly before or during the rim rolling stage and can also be found in cups with otherwise good seams displaying a full fiber tear. Incomplete side seams can occur when the temperature or ultrasonic activation time is inadequate, or if the seaming pressure is uneven. During the test runs it became apparent that the top part of the side seam receives the least heat, which could be seen clearly in thermal footage of side sealing. Insufficient cooling before rim rolling may also cause this defect, but it seems to be unlikely barring very high production speeds.

Improper blank positioning may cause a folded side seam in which the lower seam surface folds as a result of catching onto the upper seam surface as seen in Figure 26, resulting in a thicker, narrow side seam. The failure in overlapping the seam surfaces is likely caused by off-center blank positioning or a high friction factor of the cupstock. A cup with this defect can be seen in Figure 27.

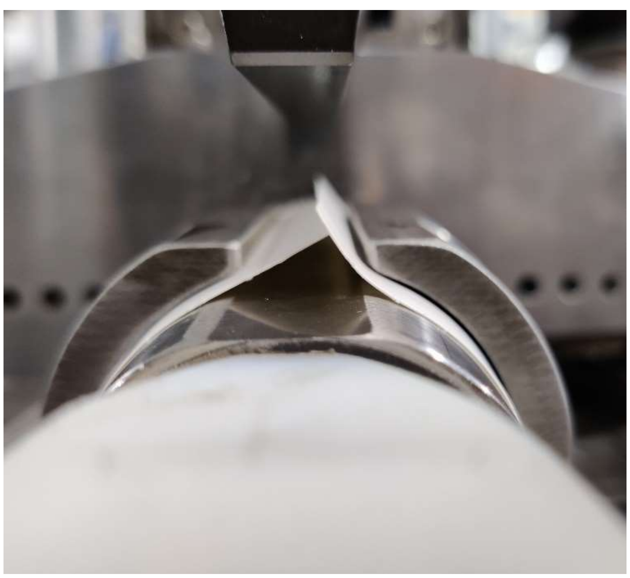


Figure 26. Example of a cup blank positioned on the mandrel in a way which could lead to a folded side seam.

Figure 27. Folded side seam and rim roll on a defective cup

This defect heavily affects the dimensions of the cup, likely causing the rest of the forming process to fail. In the defective cup in question, rim roll forming has failed due to the cup not fitting properly onto the mold, resulting in a folded rim roll in addition to the original defect.

In addition to process parameters, material condition and properties also affect the defects found in the cups. Split rim rolls are a defect most often caused by low moisture content in the cupstock. Dryness causes the paperboard to act in a stiffer manner, causing the rim roll to split while being tucked, an example of which can be seen in Figure 28. Paperboards with higher bending resistance in the cross direction (CD) are more susceptible to split rims.

Figure 28. Split rim roll caused by dry cupstock. 2-side biopolymer coated paperboard

Rim rolls can also split due to wrong cup dimensions caused by a failure in the earlier steps. For example, a failure in the curling & knurling step can increase the height of the cup, causing the rim forming steps to force too much material to be tucked into the rim, splitting it in the process. Nearly all of the previous defects can also be caused by using a material of the wrong thickness or blanks of the wrong size.

3.4 Improvements in monitoring and analysis

This section will go over the improvements implemented to the manufacturing chain and the monitoring and analysis tools trialed during this thesis. Some implementations were new additions to monitor and analyze the process, like the thermal camera, while some were aimed at improving the reliability of the process, such as the redesign of positioning tools.

3.4.1 Redesign of blank positioning

As part of this master's thesis, the tools used to stop the cup blanks in the correct position before the side seaming step were redesigned for the cup forming machine used at the LUT packaging laboratory. The purpose of the redesigned blank positioning tool was to reduce variance in adjustments by reducing the number of components in the assembly. The original system presented in Figure 29 consisted of two metal stopper pegs and two rectangular alignment parts. The pegs stop the blank in the process direction, while the aligners dictate the blank position in the cross-direction. All parts were independently adjustable, often leading to misalignment in the cross-direction resulting in multiple readjustments. Readjusting to a previously set position was also difficult.

Figure 29. Original positioning system. The stopper peg (1) and guide piece (2) have identical counterparts on the other side of the mandrel, not visible in the figure.

The updated system is based on the shape of the cup blank, dimensions matching the blank exactly, as seen in Figure 30, in which the adjustment directions are also presented. The stopper isn't 100 % symmetrical, but instead has an increased corner radius on the left corner due to the shape of the blank. The hole sizes and countersunk features were designed for the same fastening parts as the original, increasing the ease of installation.

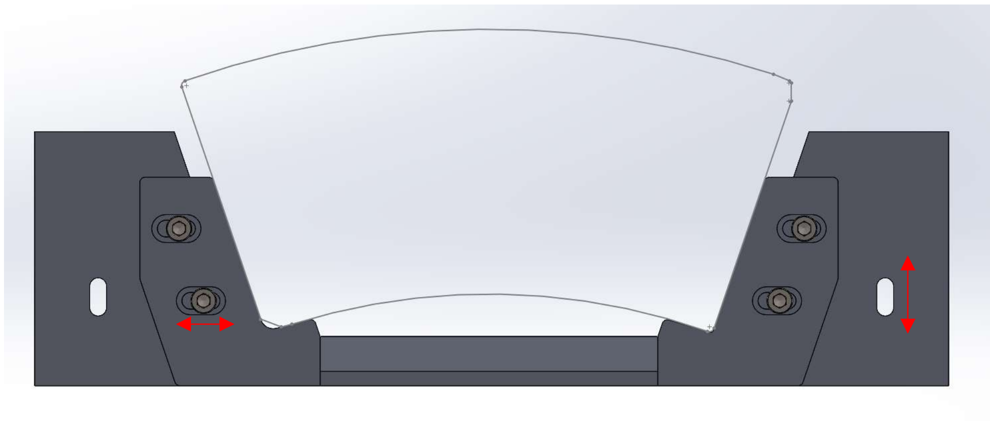


Figure 30. The tool redesign in Solidworks 2021.

The reason for the zero-clearance design is based on the nature of the process: The blank is rarely pushed into the stopper in the exact same position due to friction and variance in blank feeding, so adding clearance between the blank and stopper geometry could lead to more inconsistency. Due to the near exact match in dimensions, the blank should align itself in the stopper with the help of the push finger, also visible in Figure 29. The new blank positioning tools can be seen in Figure 31.

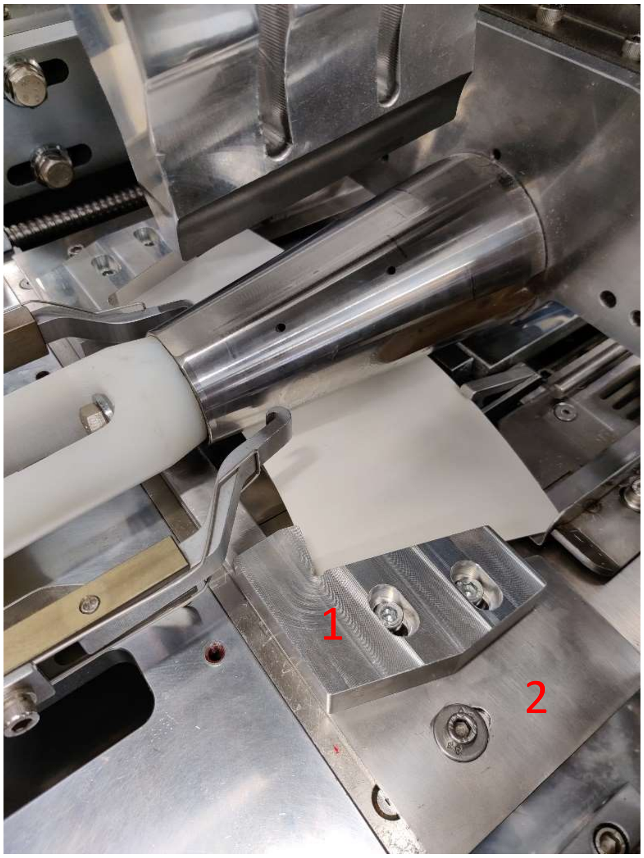


Figure 31. New blank positioning tools composed of fastening plate (1) and blank stopper (2)

The new positioning system is composed of two parts instead of the four independently moving ones. Adjusting the positioning of the blank on the new system requires moving fewer parts, since the parts moving in either direction are joined. In addition to this, the blank position is adjustable in the x-direction without accidentally affecting the y-positioning and vice versa. The new parts could be installed to the machine with minor modifications to the original construction: six holes were drilled to the base plate, two of which were tapped for fastening purposes.

3.4.2 Thermal monitoring

Monitoring certain parts of the process by using a thermal camera proved to be a very effective method of evaluating the performance of both the materials and the machine, especially relative to its setup time. Multiple heated and non-heated elements of the process were analyzed during the test runs to evaluate the effectiveness of thermal monitoring. The most crucial information gained from the thermal imagery were related to heater placements; both the bottom and side heating arrangements were adjusted as a direct result of monitoring the process. The imagery used as a starting point for the side seam heating adjustment is presented in Figure 32. The x-axis of the figure represents the length of the side seam, while the y-axis represents the temperature at points along the seam.

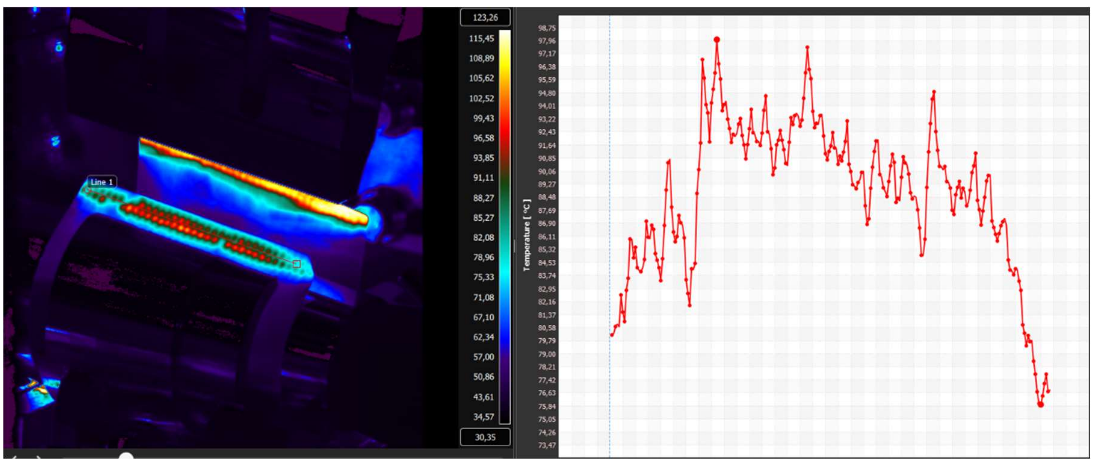


Figure 32. Side seam temperature after hot air heating pre adjustment. (Right-hand graph: highest temperature ~ 98 °C and lowest temperature ~ 76 °C)

The pattern of the hot air vents can easily be seen on the blank, making it clear the blank position is incorrect. The positioning error was identified to be caused by the hot air pushing the blank out of the way of the vent, causing improper heating. This positioning error was corrected by fixing a metal bar onto the blank feeding track to force the blank down during heating, seen in Figure 34. The improvements to seam heat can be seen in Figure 33. The most notable change being the temperature increase near the top of the side seam (left end in figure). Low seal area temperature near the top can cause the side seam to open before or during the rim rolling stage, resulting in a defective cup.

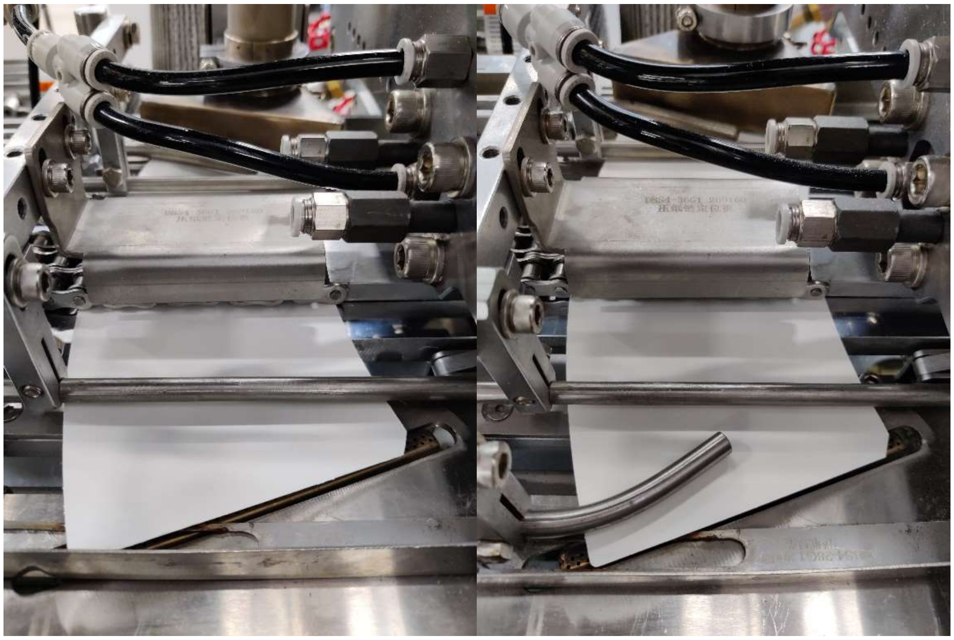


Figure 33. Before and after (left and right, respectively) installation of the metal bar to prevent the blank from rising during heating.

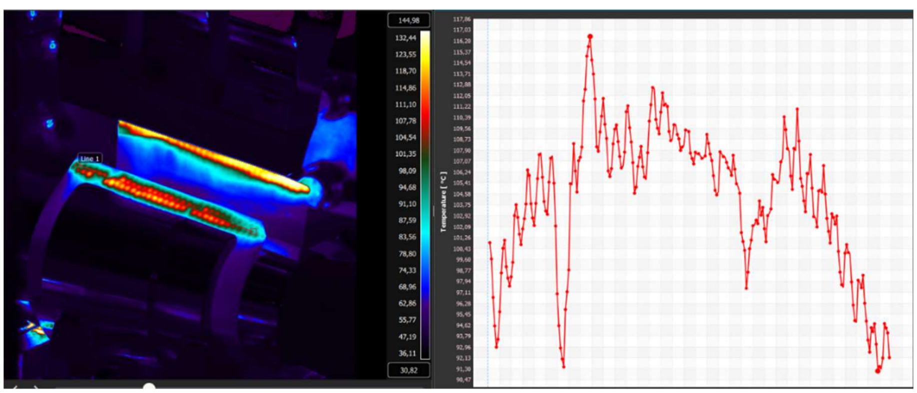


Figure 34. Side seam temperature after hot air heating post adjustment. Average reached temperature was increased by ~ 20°C. (Right-hand graph: Highest temperature ~ 116 °C & lowest temperature ~ 92 °C)

Tracking of specific cup blanks in thermal footage was tested by marking the blanks with a generic silver marker before feeding them into the process to be imaged. The silver marker was chosen due to the metallic particles possibly being reflective enough and/or absorbing more heat during the process than the paperboard surface, thus appearing visible in the footage. A set of marked and unmarked blanks were run through the forming process and filmed via a thermal camera. Figure 35 displays a marked blank going through the side sealing stage.

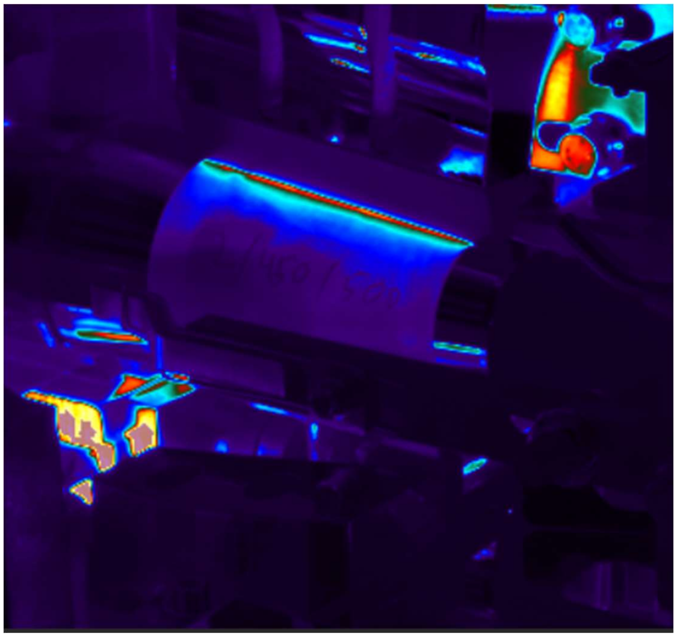


Figure 35. Thermal imagery of a marked cup in the side sealing step. The marking reads "2/450/500".

The silver marker could be used to identify the cups in the thermal footage and any desired text e.g., sample numbers, material identifications or process temperatures could be read clearly enough, especially with some adjustments to the images. The silver marker seemed to have no negative effects on the forming of the test cups, nor did it leave any traces on the blank track or tools. A more conventional option would be to use a pen with "invisible" ink which is reactive to the wavelengths used in infrared cameras. Due to time constraints and easier availability, the silver marker was used.

Sample identification could be used in combination with other analysis methods to improve their accuracy or enforce any findings, as the samples in the thermal imagery could be differentiated from each other. It could be used to, for example, try to find the root cause of a cup defect by filming different stages of the process, comparing the imagery with the finished, traceable cups.

Additionally, the temperature of the sonotrode was monitored to determine whether the machine surfaces and tools would warm up significantly during use due to hot air and blanks, and if it had any effect on the quality of the formed cups. The thermal imagery used to evaluate the warming effect is presented in Figure 36. To assess the effects of the sonotrode warming up, cups were chosen from both the cold and hot runs to be used for fiber tear tests.

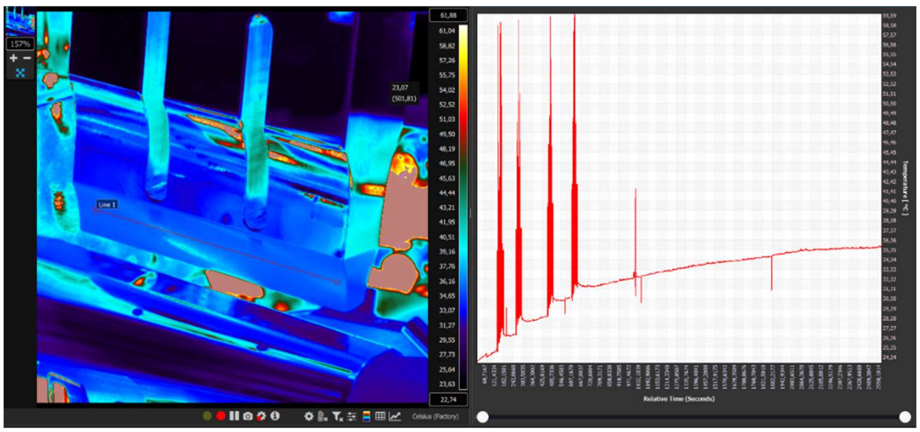


Figure 36. Temperature of the seaming sonotrode during and after (machine still running) producing cups over 45 minutes.

In the figure, the manufacturing cycles seen as spikes in the temperature chart cause the sonotrode to heat up by multiple degrees, from room temperature of about 23 °C to 35 °C during one hour of cup forming. The residual heat from the hot air vents used for side and bottom heating cause the machine temperature to rise even after stopping manufacturing. The increase in sonotrode temperature had a minor effect on side seam quality, as seen in a comparison of two seams in Figure 37.

Figure 37. Torn side seams of cold run (left) and hot run (right) with added dyed soap water displaying the portion of fiber tear.

The figure shows a slight improvement in the portion of fiber tear after a warm up of 12 °C. As the sonotrode will always heat up as a result of the machine’s residual heat while running without affecting the quality of the seam negatively, letting the machine heat up before each production run could be beneficial to improve consistency.

3.4.3 Scanning electron microscopy

The scanning electron microscope (SEM, HITACHI SU 3500) was used to investigate specific regions of interest in cups manufactured from 7 materials with different types of coatings, 3 of which were the experimental materials. Variable process parameters were used for comparison reasons. The sample regions included the cup bottom’s double seal, side seams, cup bottoms/knurling, cup walls and rim rolls. The sample cups and their imaged parts are listed in Table 5.

Table 5. SEM trial samples

Sample number	Sample material	Sample location
1	Experimental PE 1	Bottom knurling
2	Experimental PE 2	Side seam
3	Experimental PE 3	Bottom stock
4	Dispersion 1S	Bottom stock
5	Bio 1S	Side seam
6	PP 1S	Bottom stock
7	1S PE 1	Bottom knurling

Points of interest related to forming could be viewed comfortably at magnification levels of 50-150x, while close-up images of material attributes like pinholes as seen in Figure 38 would require magnifications up to 1000x.

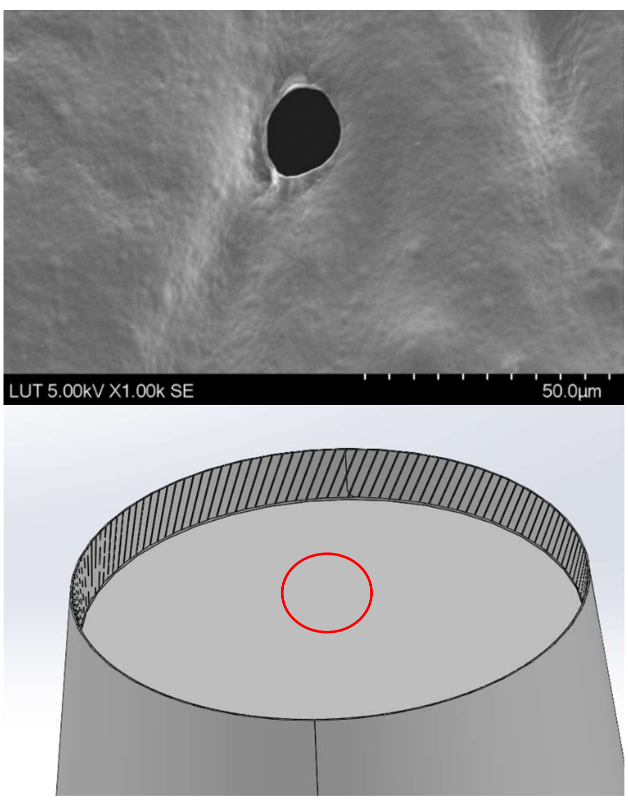


Figure 38. Pinhole (diameter ~20 µm) found in dispersion coated bottom stock (sample 4). Bottom image details sample location.

Pinholes are commonly found in dispersion coated materials due to the low thickness of the coating and were most likely formed during material production instead of cup forming as they were found in the middle region of the cup bottom. Pinholes could only be found in the dispersion coated materials in this SEM experiment. Other interesting surface defects were found on the PP-coated board, seen in Figure 39. The sample location is the same as in figure 31 seen previously, the middle of the bottom of the cup.

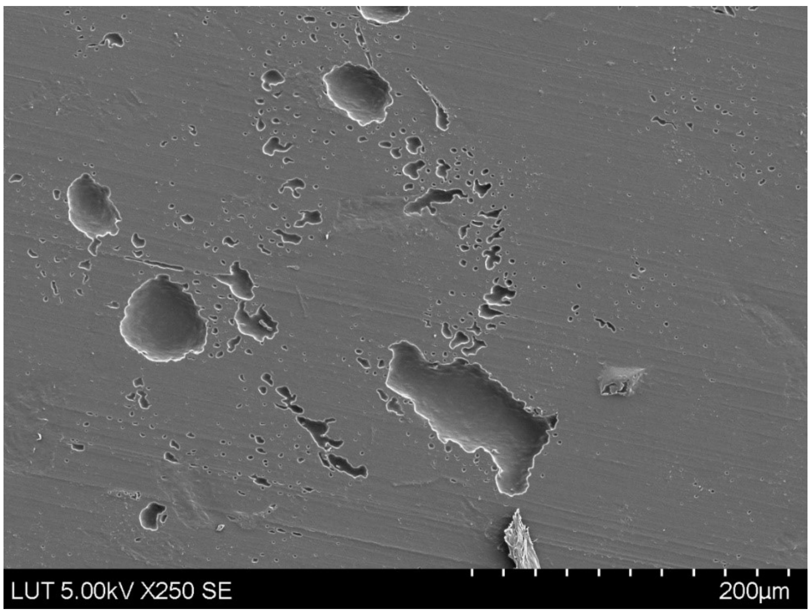


Figure 39. Porosity found on PP-coated bottom stock (sample 6)

As seen in the figure, the pores found on the coating/board range in diameter from a few to a hundred µm. The depth of the pores cannot clearly be seen from the images, but it’s likely they can’t reach the pulp layers, causing no adverse effects to the board.

In addition to surface imaging, cross-sections were also imaged. In the cross-section images, fiber and polymer layers of the seams could easily be differentiated. Some samples suffered minor damage during sample cutting, causing the top layers to fold over the surface to be imaged, reducing the viewing area. In Figure 40, a cross section of a PP-coated cup’s side seam can be seen. The side sealing temperature for this specimen was low, only 350℃, which would result in a partial fiber tear according to Figure 17.

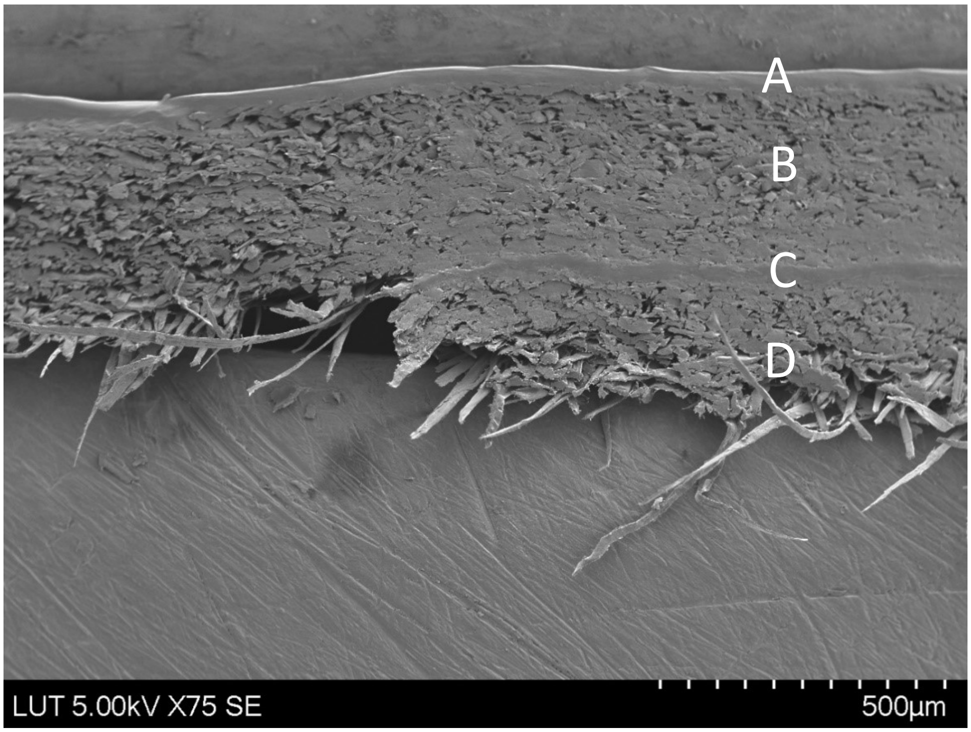


Figure 40. Cross-section of a PP-coated cup's side seam.

The topmost layer (A) seen in the figure is the inside barrier coating, followed by the baseboard (B), the polymer seal layer (C) and finally the outside board (D). The fiber orientation of the board is also visible in the cross-section, showing MD-oriented fibers along the height of the cup. Imagery of the cup’s formed bottom included imagery of the knurled seal area as well as imagery of the bottom flange. In the bottom seal area, the effect of heating the polymer can be clearly seen in a comparison of two cup bottoms formed with different parameters, presented in Figure 41.

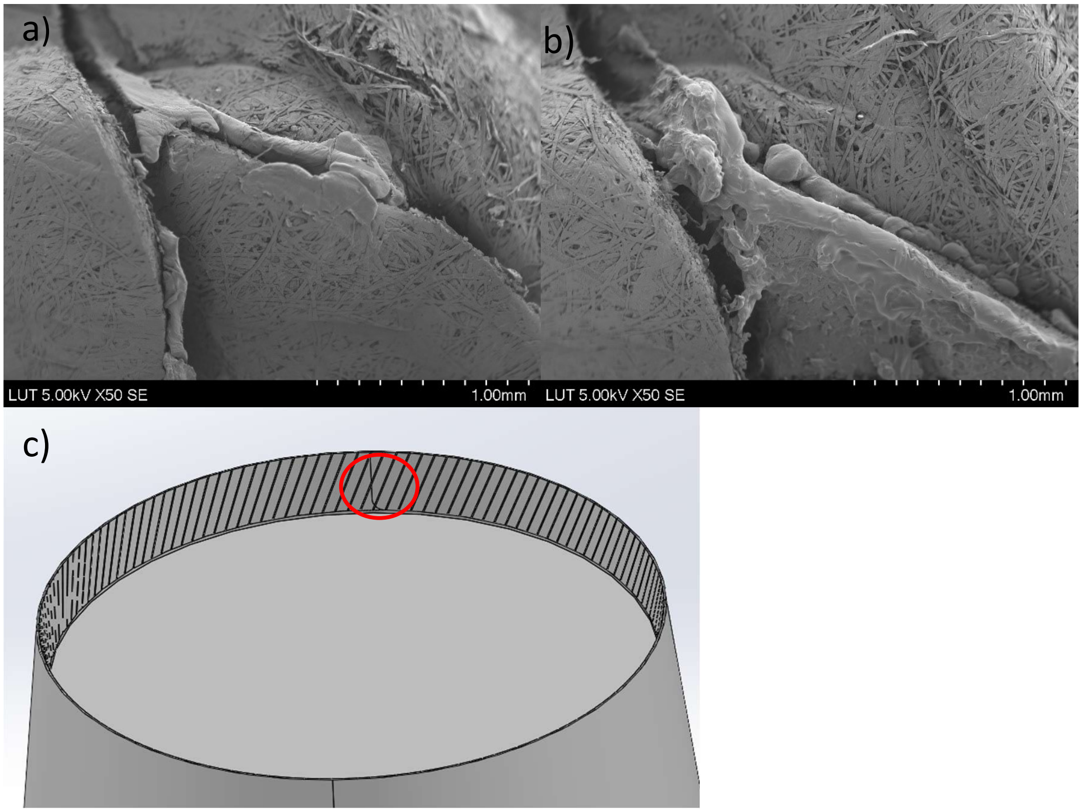


Figure 41. A 50x magnification of the knurled bottoms of two PE-coated cups (samples 7 & 1). Bottom heater temperatures of 350 °C and 500 °C were used for samples a) and b), respectively. Location of the samples shown in image c).

The bottom formed in higher temperature shows higher migration of molten polymer coating out of the seal surfaces. This is expected, as a bottom heater temperature of 350 °C is too low to reliably form full-fiber tear quality bottom seams. The images also show the borders between the ridges of the knurling, which is the part the molten polymer has been squeezed out of. The knurled bottom’s flange (the part the cup stands on) was also imaged and is presented in Figure 42.

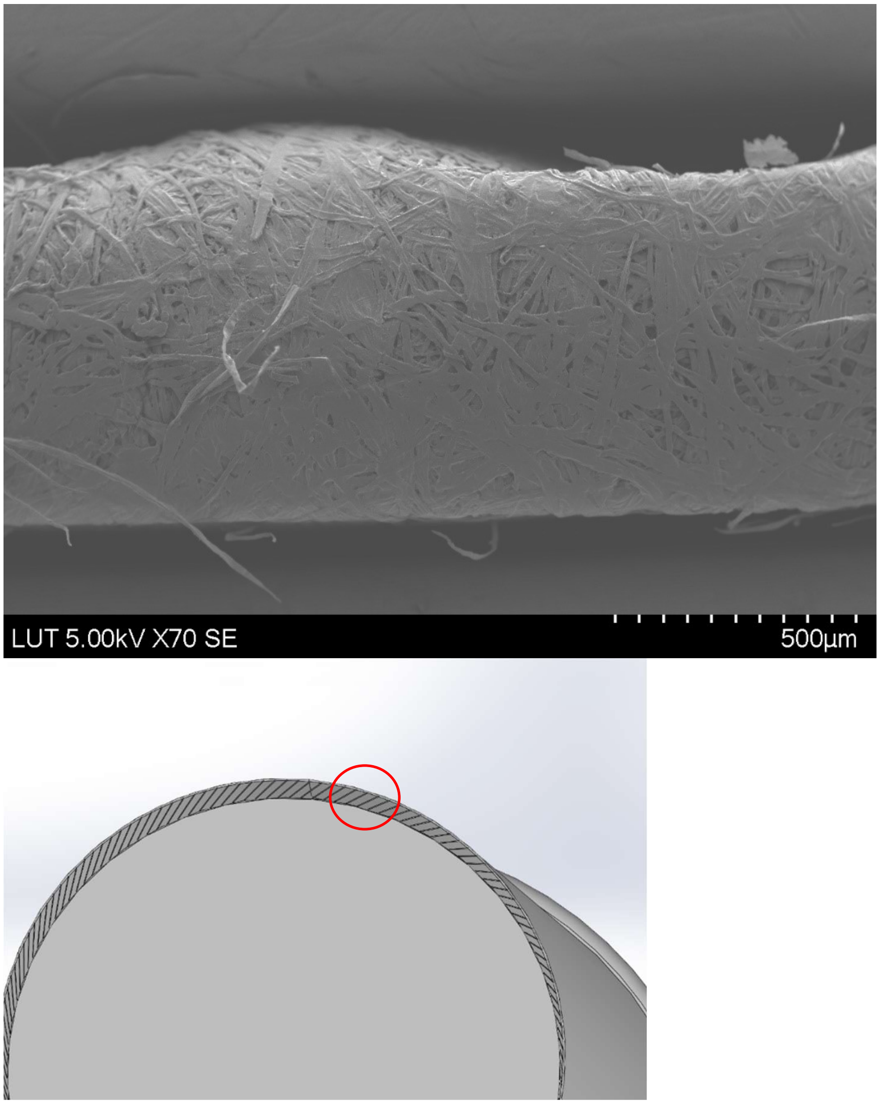


Figure 42. 70x magnified perpendicular image of cup bottom flange (Sample 3). Two contours caused by the knurling stage can be partially seen. Region of the sample circled in red.

The bottom flange fold looks fairly clean with only a few loose fibers sticking out of the surface. As the imaged area is made of the outer surface of the cup wall folded over the bottom blank and the material is single coated, all surfaces seen in the figure are fiber surfaces.

The microscopy trial itself was successful, but more specific comparisons should be made to find final use cases for SEM-imaging in cup analysis. A reasonable approach would be to use a regular microscope and a smaller magnification level when investigating cup material behavior or defects due to the material preparation time required for SEM-samples. Electron microscopes reach magnification levels which are unnecessarily high for the type of findings that could be analyzed in cup seams, for example.

3.4.4 Magnetic thickness measurement

A magnetic thickness measurement device, the Magna-Mike 8600, was used on the side seam and bottom knurl areas as part of the analysis of formed cups. The device measures thicknesses of non-ferrous materials by measuring the distance between a small target ball and the magnetic probe. The device works for measurements from 0.001 mm up to 25.4 mm, making it suitable for analyzing paperboard cup materials, the material thickness of which usually varies from 0.25 mm to 0.35 mm. A possible use for the device would be evaluating the amount and consistency of seaming pressure through flattening of the materials at the seam areas.

The device was used as a trial to measure two sets of cups, one manufactured with ultrasonic side sealing and the other with hot air to find any differences. The principle of the measurement process can be seen in Figure 43. Measuring the thickness of the side seam at the middle point, while the results of the measurement trial can be found in Table 6.

Figure 43. Measuring the thickness of the side seam at the middle point

Table 6. Results of the thickness measurement trial

	Average seam thickness [mm]	
	Hot air sealing	Ultrasonic sealing
Top	0.569	0.486
Middle	0.571	0.483
Bottom	0.572	0.489
Standard deviation	0.0039	0.0081

As seen in Table 6, the difference in resulting thickness between the sealing options is notable, ultrasonic sealing causing the material to compress an additional 0.08 mm compared to hot air. The standard deviation of the test results was quite low, making this a viable option for thickness control. In later research, it could be worthwhile to investigate the connection between the compression force of the sonotrode and the resulting seam thickness by using the thickness measurement device.

3.5 Discussion & research suggestions

Seven of the eight reference materials were able to be formed into defect-free, liquid proof cups at the maximum production speed of 140 cups per minute. The problematic material, coated on both sides with a dispersion barrier coating, had trouble reaching a full-fiber tear at maximum production speeds, possibly due to the thermal sensitivity of the coating. A full-fiber tear could be reached by slowing the production speed by almost 50% to 80 cups per minute. The material would likely benefit from increased cooling during or after the side seaming step, which would cause the coating to adhere in a shorter time at higher production speeds. An incorrect clearance setting in the side seaming step may also have contributed to the sealing issues, as dispersion coated materials tend to be more sensitive to incorrect parameters and mechanical adjustments.

The experimental test runs were successful, managing to produce defect-free cups out of each corresponding wall & bottom combination. The overall pinhole forming sensitivity of the experimental materials was found to be less than that of a commercial cup material, which was likely caused by the experimental material's slightly higher PE coating grammage. In pinhole testing, the gradual slow-down of the machine while stopping caused the blanks to linger in the heaters longer than intended, causing increased heat transfer to the sealing area. Removing the bottom forming tools following the bottom heaters would reduce or remove this effect, causing the results to be better comparable to actual process conditions. For this thesis, however, this would have been too time consuming as it would have required the tools to be reinstalled and adjusted each time after removal. The method used to isolate temperature for pinhole sensitivity had some promising outcomes despite some variance in the sets. At its current iteration, it could be used to compare known materials to new, experimental materials to find differences in temperature sensitivity.

The blank positioning tools were redesigned based on the shape of the cup blank, machined, and installed to the cup machine. The redesign was successful, as the new positioning tools improved the predictability, consistency, and accuracy of adjusting the side seaming stage. Due to the fixed style of the new tools, however, they can only be used on blanks shaped similarly to the one it was based on, limiting their uses.

The SEM-findings made during the thesis were interesting, but the extreme magnification levels of the SEM were shown to be quite excessive for the application. The sample selection could also have been improved, as some high sealing temperature samples were chosen from regions not actually affected by the heat during the process. While these magnification levels could be used to find defects in the materials themselves, lower levels would have sufficed for analyzing the seal surfaces, defects and damage done by the processes.

Thermography was directly used to improve the machine’s sealing performance based on the footage and to compare set temperatures to actual reached ones. The possibility of marking and tracking individual blanks in thermal footage with a generic silver marker was found to be feasible and could be used to track certain stages of the process in greater detail by combining thermography with an analysis method, e.g., microscopy, and will be an integral part of further research dealing with any heat factors.

The main point of improvement would have been increasing the number of reference results and comparison points available in some of the shorter trials like magnetic thickness measurements. Completing additional tests could have increased the reliability of the trials. The significance of the combined effect of heat and friction was highlighted in the experiments in the form of runnability problems: when running some materials at sealing temperatures near to or higher than their usual maximum sealing ranges, the residual heat from the side seam heaters increased friction to a point where the blank could get stuck on the mandrels. The effect of friction in the whole process is a complicated matter, as it is always a phenomenon between two interfaces and is affected by both their properties, which are again affected in different ways by factors like humidity and temperature. Investigating the effect of different surface materials in the process could be advantageous.

4 Conclusions

The goal of this master’s thesis was to develop the processes used to analyze and monitor the cup manufacturing chain at the laboratory of packaging technology at LUT University. This was achieved through a literature review on cup manufacturing and an experimental part in which both reference and experimental materials were formed into cups to trial different analysis and monitoring tools. As demonstrated by the results, it’s possible to form even more challenging materials into defect-free cups by applying knowledgeable adjustments to the process, the experience for which could be attained rather quickly by running and optimizing different materials with varying coating types, provided the runs are appropriately planned and documented. Thus, the goal of the experimental runs was met. Material stiffness, friction factors and the melting point of the coating all affect the manufacturing chain and should be considered when adjusting the process if defects or runnability errors are encountered.

The trialed monitoring and analysis methods together with the improved blank positioning tools were deemed useful in process adjustment as well as material comparison and analysis, which could accelerate the take-up of novel materials through better predictability. Designing specific tools for blanks of different sizes should be considered to increase consistency and accuracy, especially in a research environment where frequent adjustments are required. The thermal camera proved itself to be the most useful and versatile monitoring tool due to the possibility to combine it with other analysis tools like microscopy. In addition, it facilitated process correction in the seaming stages, as uneven or insufficient heating could previously only be seen indirectly via seam quality. The pinhole analysis method and thickness measurements should be considered in future test runs as they showed promising results and consistency in the trials. The magnification levels of the SEM felt excessive during the trials, but due to the clarity of the images it could have uses in investigating material behavior. The traditional analysis method of the industry such as fiber tear tests and liquid tests held their own among the trialed ones, but they could see some improvements in the future; namely the fiber tear test of the bottom, as cups can be liquid-tight even at partial fiber tears. Nevertheless, they have their uses as preliminary tests in research before moving on to more specific analysis tools. To conclude, the thesis shed light on the relevant sub-processes and phenomena concerning the whole cup manufacturing chain.

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