# INVESTIGATING THE PRACTICALITY OF ULTRASONIC SEALING FOR FLEXIBLE FIBER-BASED MATERIALS AS A LIDDING FOR PAPER CUP APPLICATIONS

Lappeenranta–Lahti University of Technology LUT

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ABSTRACT

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**Investigating the Practicality of Ultrasonic Sealing for Flexible Fiber-Based Materials as a Lidding for Paper Cup Applications**

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Keywords: ultrasonic sealing, paper-based material, thermoplastic film, OPP+PE, Paper+PE, dispersion coated paper, seal strength, paperboard cup, leak test.

The use of thermoplastic materials for packaging end-uses has been on the rise since its inception, contributing tremendously to the overall plastic production. Among various sealing methods, ultrasonic sealing is renowned for its energy and material efficiency; however, much of the published research focused on ultrasonic sealing of thermoplastics rather than paper-based materials. The motivation of this study was to reduce thermoplastic usage in the packaging industry by promoting paper-based materials as an eco-friendly alternative. The main objective was to investigate the usage of paper-based material as lidding for paper cups. The materials used consist of: OPP+PE, Paper+PE, and dispersion coated paper. The research was composed of two parts: testing the seal strength of the materials and to conduct a leak test on paper cups with lids made from the same materials. All test samples were sealed using an ultrasonic sealer, with four main sealing parameters: weld time, hold time, amplitude, and pressure. Together they affect the final output -seal strength or leak tendency- in complex ways. Results indicate that all three materials achieved acceptable seal strengths: OPP+PE at 50N, Paper+PE at 10N, and dispersion coated paper at 5.3N. Notably, OPP+PE showed significantly higher seal strength than Paper+PE and dispersion coated paper; this was due to the latter containing only 12% plastic in weight, while OPP+PE is at 100%. Although the cup lids passed the leak test, the range of sealable parameters was slim. To add, there were many types of failures that increased the chances of leakage: cup delamination, cup getting stuck to the anvil, damage to the cup's PE-coating, and wrinkle formation lid due to pressure variation. The study examined these problems and found solutions, work around, or explanations. Several suggested improvements and suggestions for future tests are further discussed.

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Abdulaahi Mohamed

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# SYMBOLS AND ABBREVIATIONS

## Roman characters

| | | |
|---|---|---|
| *amp* | Amplitude | m |
| *hT* | Hold time | s |
| $T_g$ | glass transition temperature | °C |
| *wT* | Weld time | s |

## Abbreviations

| | |
|---|---|
| ASTM | American Society for Testing and Materials |
| OPP | Oriented Polypropylene |
| PE | polyethylene |
| PVA | Polyvinyl Alcohol |
| p-value | predictive value |
| US | Ultrasonic sealer |

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# 1 Introduction

Studies show that the majority of produced plastic has always been for packaging end-uses (OECD. 2017). Continues efforts are made to advance the alternatives, and this research was conducted in the hopes of contributing to that. The following chapter provides the background and discusses the motivation as well as the objectives of the research.

## 1.1 Background

Ultrasonic welding was first developed by Robert Soloff in the 1940s. It uses ultrasonic acoustic vibrations to achieve efficient and precise seals. Ultrasonic welding is used in many fields, such as aerospace, medical, and food packaging industries. While ultrasonic sealing technology has thrived in plastic packaging, the environmental concerns regarding the usage of plastic as a whole have grown to be more pressing. This issue is important since the packaging industry is and has always been the biggest contributor to plastic production (Figure 1). This shift in environmental concerns is particularly evident in governmental regulations on packaging waste and materials. The pursuit of eco-friendly packaging solutions is not only driven by the regulations but also by the increased awareness of consumers who are willing to pay a premium to support the environment. A promising yet underutilized alternative is fiber-based materials. These materials offer eco-friendly qualities that resonate with the current demands.

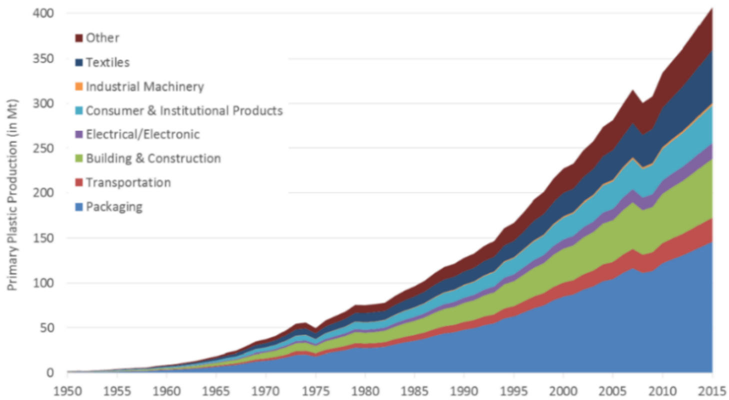
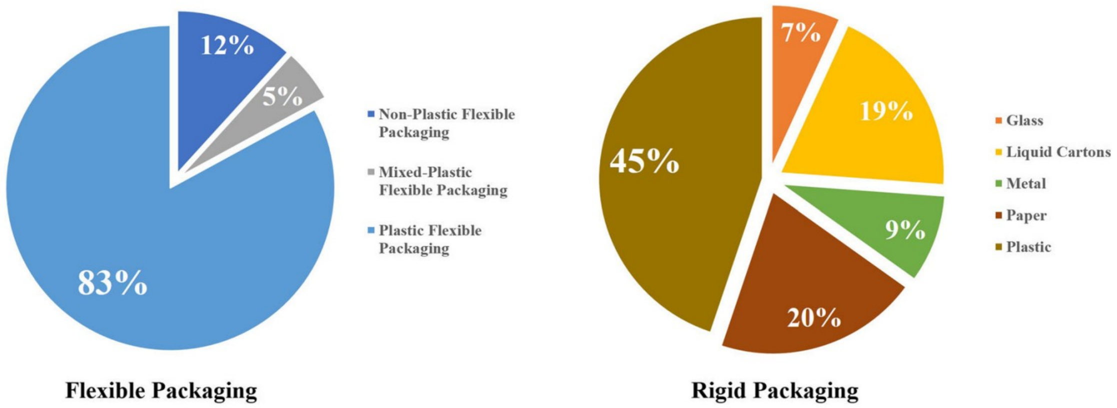



Figure 1. End uses of produced plastics (OECD. 2017).

The material mostly used for packaging material is plastic which is 45% in rigid packaging; and for flexible packaging materials, it is 83% (Figure 2). The negative effects it has on the ecosystem have been one of the hottest topics of this century.




Source: Euromonitor International (2020). Data Set: "Food Packaging World", Year 2019 Note: "Mixed-Plastic Flexible Packaging" includes packaging materials where plastics are not the base material but are incorporated to improve the base material's properties (e.g., aluminum/plastic, paper/plastic)

Figure 2. Euromonitor International (2020) cited in (Jovan & Sandeep Kumar & Seeram 2021, p. 3).

## 1.2 Motivation

The motivation behind this research is partially rooted in the increased awareness of the lasting negative effects associated with common plastic packaging material, as well as the desire to improve the performance of potential alternative materials and methods. The use of fiber-based materials has emerged as an attractive alternative. With the right components, not only is it recyclable but it also attracts conscientious consumers who are willing to pay premiums in the hopes of preserving the environment.

The motivation of this thesis is to evaluate and optimize the performance of ultrasonic seal for fiber-based. An extensive literature review reveals that there has been very few research done on ultrasonic sealing of paper-based cups with fiber-based material used as a lidding material. This study aims to fill this research gap and contribute to sustainability efforts.

## 1.3 Research Problem and Questions

Ultrasonic sealing for thermoplastic materials has been extensively studied. However, research on the usage of fiber-based material as lidding for paper cups is relatively scarce. As environmental concerns and regulatory shifts push the packaging industry toward sustainable solutions, the potential of fiber-based materials becomes increasingly evident. Furthermore, according to Charlier, Viguié, Harthong, Toni, Terrien, Imbault & Peyroux (2021, p. 892), no established framework exists for determining the optimal parameters for ultrasonic sealing; therefore, a trial-and-error approach is required for each family of material.

The main research questions are:

- Can ultrasonic welding be used to seal the following materials: dispersion coated paper and PE extrusion-coated paper?
- Can flexible fiber-based materials be implemented as a lidding application for paper-based cups?
- What are the challenges of using an ultrasonic sealer to seal fiber-based materials?

The sub-questions are:

- What are the parameters that yield an acceptable or alternatively the highest possible peel strength?
- What is the effect of each individual parameter of the ultrasonic sealer?
- What is the percentage of contribution of each parameter in affecting the seal strength? Which parameter passes the null hypothesis?
- Do both materials require similar welding parameters or not? If there is a difference, what is the cause for that?

## 1.4 Scope

The research is composed of two parts:

The first part of the research is to evaluate the seal strength of certain flexible fiber-based materials. First, a literature study will be undertaken to cover as much relevant information as possible. This will be helpful in having an expected result. After that, a preliminary test will be performed to identify the parameters that significantly affect the outcome as well as the ranges of sealing parameters. The primary focus will be on seal strength, to achieve the highest possible strength using the available equipment. Comprehensive testing will be conducted in the defined ranges with a meaningful resolution. Failures and phenomena are expected to arise, and further research is planned on previous literature to see if these problems have been faced before and try to come up with reasonable explanations.

The second part of the experiment is about sealing the cup with the same fiber-based materials and conducting a leak test. In a similar fashion, a literature study will be conducted. The ranges will be defined and tested. The hypothesis is that the cup sealing is going to be more complicated as it involves more variables, but that also means more phenomena to encounter. Unlike the first part of the research, the goal is to find a sealable range instead of trying to find a higher numeric value.

# 2 Literature review

The thesis covers two main topics which are ultrasonic welding and flexible fiber-based materials. There are other minor topics related to the thesis, these topics are thermoplastic, heat sealer, hot-tack, and cold-tack. To advance any topic, it is important to understand the current state of research in the field. This literature review aims to provide a comprehensive overview of the latest research on ultrasonic sealing of paper as well as thermoplastics to enhance understanding of the subject. This review evaluates the relevance and applicability of the findings from selected studies and reports for the project.

Menges & Potente (1971) researched the mechanism for heating and they concluded that the main heating effect in the ultrasonic process was a result of viscoelastic heating. Prior to their study, researchers believed that the heating mechanism was from interfacial friction. However, through simulation and experimental research, Zhang, Wang, Luo, Zhang & Wang (2010) found that it is a combination of both; the interfacial friction initiates the temperature rises at the corners of the contact point that is until it approaches Tg. After that, viscoelastic heat becomes the main source of the heat mechanism. (Zhang et al. 2010, p. 648, 663.)

A study on thermoplastics has been done by Marcus & Prior (2016); They found out that non-pigmented material requires less energy compared to colored material. Additionally, they also displayed higher peel strength. They also found out that films containing foil showed greater peel strength compared to those without. This could be because the foil transmits heat more effectively. (Marcus & Prior 2016, p. 1342.)

According to Mediana (2018), controls of an ultrasonic sealing device are more forgiving because they offer better flexibility in terms of parameter input compared to thermal sealing (also known as contact heat sealing) which has 3 parameters: heat energy, pressure, and time; All three of these factors must be tightly controlled for maximum consistency and small variance may cause failure. However, the ultrasonic sealing process offers more ways to control the energy that can go into each seal individually; those parameters are force (pressure and down speed) and velocity (frequency and amplitude). The amplitude, measured in the horn’s peak-to-peak movement, is adjustable to generate the necessary mechanical waves of energy for bonding the materials together. This allows for precise regulation of the melt temperature at the seal interface, which is impossible with heat bars used in thermal sealing processes. Ultrasonic welding offers a wider range of solutions for challenging sealing problems. (Mediana 2018, p. 13.)

Charlier et al. (2021) found that in ultrasonic sealing, four parameters are the most impactful: vibration, amplitude, power, and thickness of the paper. Moreover, these parameters are intertwined and may have a direct effect on the sample's property or affect indirectly through other parameters. They also found out that increasing Pm (power peak) increases the seal strength till it reaches the maximum weldability of the material. Exceeding the power over the maximum weldability results in the sample being burned. As for the case of amplitude, it affects the reproducibility of the experiment, increasing the amplitude decreases the reproducibility and vice versa. It was noted in the study that the maximum performance does not change with amplitude, but the average mechanical performance decreases instead. The study also found that increasing the thickness of the film increases the seal strength. Parameters that did not have a noticeable effect were the amount of energy, welding speed, and post-welding load. After discussing all the different important parameters, Charlier, et al. state that despite all these findings for ultrasonic welding, there is no global model that can determine the appropriate parameters for the machine and the acoustics based on the thermoplastic parts to be welded. (Charlier et al. 2021, p. 892, 900-905.)

Marcus & Prior (2016) had already done research on OPP+PE (one of the considered testing materials). The results of this research were generated using fixed welding parameters for all materials instead of varying ones. This was because the focus of the test was to investigate the performance of different anvils, rather than examining optimal parameters for reaching the highest seal strength. Notably, one of their findings was that the weld quality significantly depends on the strength of the film being welded. (Marcus & Prior 2016, p. 1336, 1339.)

Merabtene, Tanninen, Varis & Leminen conducted research on heat sealing of paper in VFFS machines. Their research utilized similar materials to the ones intended for use in this thesis (OPP+PE, Paper+PE, and dispersion coated paper). One of their findings was that thermoplastic materials on average had 3 times higher peel strength than fiber-based materials. (Merabtene, Tanninen, Varis & Leminen 2022, p. 239.)

According to Ward & Kazakov (as cited in Marcus & Prior 2016, p. 1336), the weld area can maintain its structure better when it has polyethylene sealing layers. This is because these layers have a broad molecular weight, distribution, high toughness, and low zero shear viscosity.

Regazzi, Viguié, Harthong, Dumont, Imbault, Peyroux, Rueff, Charlier, Guérin, Leroy, Krouit & Petit-Conil. (2019, p. 12939) investigated the parameters for optimized ultrasonic welding on 100% lignocellulosic paper, which was the first paper of its kind released in a while. The study stated that the welding of paper occurs due to the similarity of wood and polymers when they undergo heating. (Regazzi et al. 2019, p. 12939.) “Structural analyses have revealed that the establishment of adhesion in welded papers originates from a thermoplastic mechanism.-- However, the degradation of paper also seems mandatory to generate adhesion which indicates that thermosetting mechanisms must also contribute.” (Charlier et al. 2021, p. 893).

Analyzing the structure of the welded paper, they found out that the adhesion originates from a mechanism similar to thermoplastic. This is also found in wood’s polymer components such as hemicelluloses, lignin, and amorphous cellulose; when they are under pressure the polymers tend to creep into one another and form new matrix. (Regazzi et al. 2019, p. 12939.) This phenomenon was previously studied in Gfeller, Zanetti, Properzi, Pizzi, Pichelin, Lehmann & Delmotte. (2003, p. 1588). Right after the thermoplastic mechanism, thermosetting starts to take effect. Presuming there is a high temperature, chemical reactions start to take place which further strengthens the matrix. These reactions are the same ones that cause the degradation in paper which makes it appear to be burnt. (Charlier et al. 2021, p. 892.)

According to Regazzi et al. (2019), the performance of welding 100% lignocellulosic paper is very low. However, most of the paper and paperboards in use today have additives and are coated with layers to achieve the desired characteristics for their use (Charlier et al. 2021, p. 893). Regazzi et al. (2019) paper was written to explain welding characteristics of papers in their pure form and not for practicality.

Some of the additives and coatings enhance the performance of the welding. Therefore, in ultrasonic sealing, 100% paper is not representative of the demand of the packaging industry since additives are almost always used (Charlier et al. 2021, p. 893). Some of these additives used are latex binder, which increases printability; starch for increasing strength; and PVA for better barrier properties. Charlier et al. (2021) showed that the additive that contributed to the adhesion was PVA; it melts and flows when the temperature is above the transition temperature, which enhances the performance of the thermoplastic mechanism. The researcher also found that when peeling welded joints, the failure propagation type is related to Pm (peak power). It's mostly adhesive at low Pm, but according to Charlier et al. (2021, p. 900), "it progressively changes to cohesive when Pm increases, and the peeling strength gets closer to the maximum value that can reach the material. Then, the welding process starts damaging the materials."

In paper welding, along with power and amplitude, the thickness of the paper plays a significant role. In packaging applications, working with thicknesses of 100 µm or less is common and can lead to larger standard deviations. Specifically, the seal strength depended on the residual thickness after the papers were joined. The residual thickness can be modified by changing the welding pressure or by adding static pressure before welding which eases the polyvinyl chloride to flow outside the welding zone. (Charlier et al. 2021, p. 903, 904.)

Similar to Marcus & Prior's (2016) results, Charlier, et al. also found out that for a material, a maximum seal strength exists, beyond which increasing the thickness no longer increases the seal strength. It is important to state that Charlier et al. (2021) did not test papers with different thicknesses but instead stacked them on top of each other. Charlier, et al. stated that the accuracy of the statement from his research regarding high thickness might need adjustment before reaching a conclusion. They stated that the paper thickness appears to be a critical factor because the mechanical properties deteriorate significantly when using thin papers. Charlier, et al. believed that the effect of thickness can be controlled using other methods, such as designing suitable acoustic components or altering the operating frequency. (Charlier et al. 2021, p. 903, 904.)

One advantage of ultrasonic welding is that it has a relatively small hot-tack period, and the product is ready to be used right away (Bach, Thürling & Majschak. 2011, p. 237). Hot tack has considerably less peel strength. In their research, Hauptmann, Bär, Schmidtchen, Bunk, Abegglen, Vishtal & Wyser found out that Serrated sealing jaw can be used to reduce the duration of the hot-tack of paper-based materials and polyolefin laminates, the former being affected heavily. An increase in sealing time and sealing pressure both improve the paper material's seal strength, particularly the Hot-Tack due to improved heat transfer. However, from the production point of view, a sealing time above 0.5 seconds is not economically acceptable. (Hauptmann et al. 2021, p. 10.)

Marcus and Prior (2016) experimented with several anvil shapes: male knurl, female knurl, single ridged, five ridges, and flat anvil. The experiment rig was designed in a way that the details on the horn and anvil could be interchanged. In most of the scenarios, Marcus and Prior found out that placing the sealing details on the horn or anvil makes no noticeable difference. An exception was with male and female knurls which showed higher strength when placed on the horn. Regarding their performance, the flat horn/anvil was the weakest; they assumed that it was because the surface to be bonded was wide. However, they performed best on thin material because otherwise the knurl/ridge would degrade the film due to its heat concentration. Likewise, thicker material performed best with a serrated anvil/horn. (Marcus and Prior 2016, p. 1340, 1342.)

In conclusion, the findings from the conducted literature review will serve as a guide and a reference for the proper selection of parameters during the preliminary testing and after. It will also help us have an expectation of the outcome and a deeper understanding of relevant information such as sealing mechanism, failures, and etc.

# 3 Methodology

The objective of this thesis was to test the seal strength of flexible fiber-based materials that are sealed using an ultrasonic sealing method. Second, to test the leakage of disposable cups ultrasonically sealed with the same materials as a lid. The following chapter provides in-depth details of the procedure, including descriptions of the specific materials and equipment used as well as the ranging parameter and the underlying reasoning.

## 3.1 Overview of the experimental procedure

The methodology consists of two parts: In the first part of the experiment, the sample is prepared, ultrasonically sealed, and tested according to ASTM F88. The materials used are Paper+PE, OPP+PE, and dispersion coated paper.

In the second part of the experiment, the same materials are ultrasonically sealed on disposable paper cups as lids. After that, a leak test is carried out according to a modified ASTM F3039. More information regarding the modification will be mentioned in Chapter 3.3.5.

The results from the two experiments are analyzed differently. The performance, failures, as well as improvement are talked about in the results.

## 3.2 Material properties

The 4 materials that were used for testing were OPP+PE, Paper+PE, dispersion coated paper, and PE-coated paperboard.

Table 1. Material properties

| | OPP+PE | Paper+PE | Dispersion coated paper | PE-coated paperboard | |
|---|---|---|---|---|---|
| | | | | **Baseboard** | **Polymer coating** |
| Basis weight, (g/m²) | 49.65 | 70 | 65.0 | 210 | 15 |
| Thickness, (µ) | 52 | 70 | 66.0 | 280 | 10 |

1. OPP+PE

This material is composed of a layer of Oriented Polypropylene (OPP) of 15 µm thickness, followed by layers of ink, adhesive, and Polyethylene (PE) of 35 µm thickness. The corresponding material composition is shown in Figure 3.

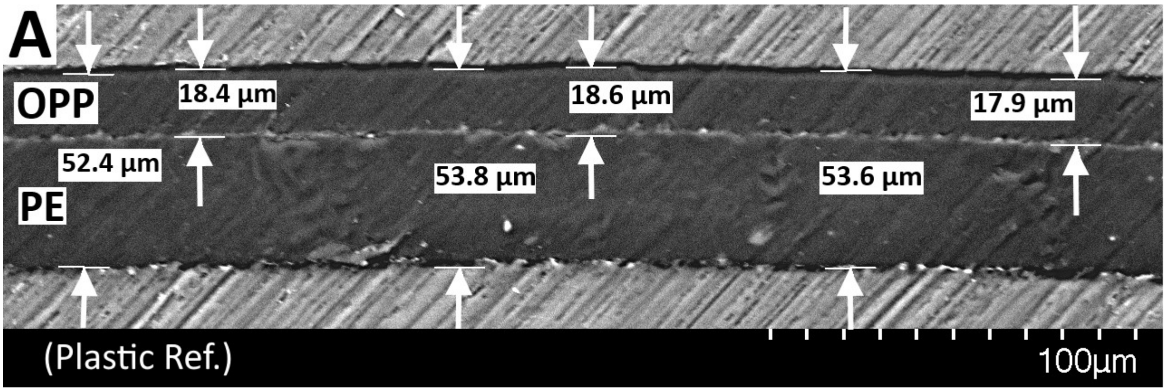



Figure 3. OPP+PE (Reproduced from Merabtene, Tanninen, Wolf, Kayatz, Hauptmann, Pesonen, Laukala, Juha & Leminen. 2023, p. 669).

2. Paper+PE

Paper+Pe is polymer-coated paper consisting of 55 µm of base paper and 15 µm of Polyethylene (PE) which is applied using corona treatment.

This material is composed of a layer of Oriented Polypropylene (OPP) of 15 µm thickness, followed by layers of ink, adhesive, and Polyethylene (PE) of 35 µm thickness. The corresponding material composition is shown in Figure 3.

3. Dispersion coated paper

Dispersion coated paper (Disp) is a heat-sealable material consisting of 60 gsm of base paper and 5 µm of dispersion coating. It offers good grease resistance, good moisture and mineral oil barrier, heat sealability, and recyclability. Intended use: lamination, pouches, sack, etc. (see Figure 4)

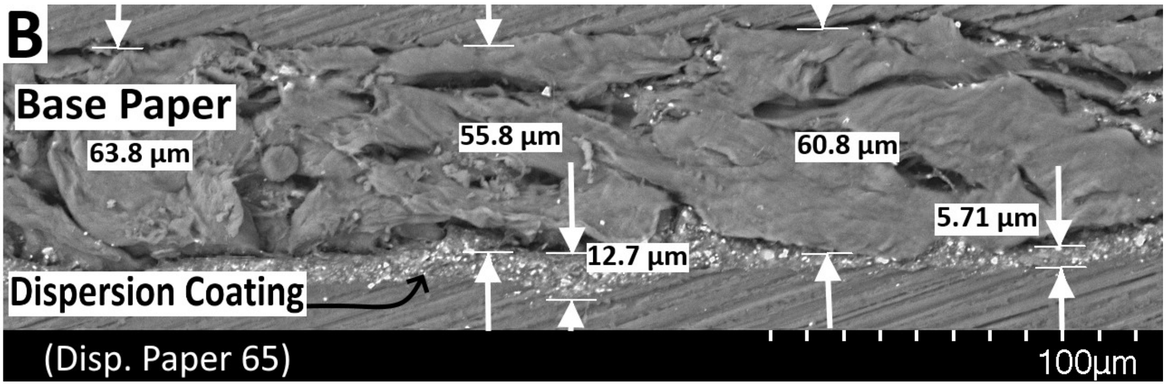



Figure 4. Dispersion coated paper (Reproduced from Merabtene et al. 2023, p. 669).

4. PE-coated paperboard

PE-coated paperboard is a multilayered material composed of bleached sulfate pulp and CTMP at the center, with bleached sulfate pulp on the top and bottom layers. The uppermost layer receives a double pigment coating, while the reverse side is coated with PE. (see Table 2)

Table 2. Material layer composition

| Layers | Material type (outside to inside) |
|---|---|
| 1 | Double pigment coating |
| 2 | bleached sulfate pulp |
| 3 | bleached sulfate pulp + CTMP |
| 4 | bleached sulfate pulp |
| 5 | PE coating |

The material is a stiff yet relatively lightweight product. It's food-safe and ecologically friendly; The disposable cups used for leak testing were made from it. It has good printing properties and can be used for different printing methods like flexo, offset, and digital printing.

## 3.3 Experimental setup

The following section details the devices and the methods used to conduct the experiment.

### 3.3.1 Ultrasonic sealing

The sealing method is ultrasonic sealing using Branson 2000x (Figure 5). Branson 2000X is an ultrasonic welding machine designed by Emerson. Of the four models available, the 2000Xd variant was utilized in the experiments. It comes with a variety of specifications which can have multiple configurations. The configuration used generates a fixed 20-kHz frequency. The US consists of a sonotrode whose height can be configured, a Horn that is attached to the sonotrode, and an anvil that is fixed with no degree of freedom albeit interchangeable.

Figure 5. Branson 2000x (Emerson [Referred 2023a]).

The amplitude from the ultrasonic machine is adjustable from a minimum of 45% to a maximum of 100%. The pressure can reach up to 6 bar. The machine's power is generated from Branson 2000x distance power supply 20:2.5. It outputs 2500 wattage and 200-240 Volt AC. With a maximum current of 14 amps.

Ultrasonic sealers are equipped with a 'horn' and an 'anvil'. When sealing the materials for seal strength testing, a horn called OF-74419 from Branson 2000x (Figure 6) was used. Following ASTM F88, a 25mm wide customized anvil was utilized to increase grip and reduce dissipation (Figure 7). The grip is increased because both the section that held the sample as well as the material itself are 25 mm wide; making it a transitional fit. This ensures that the sample does not move or slip during weld time.

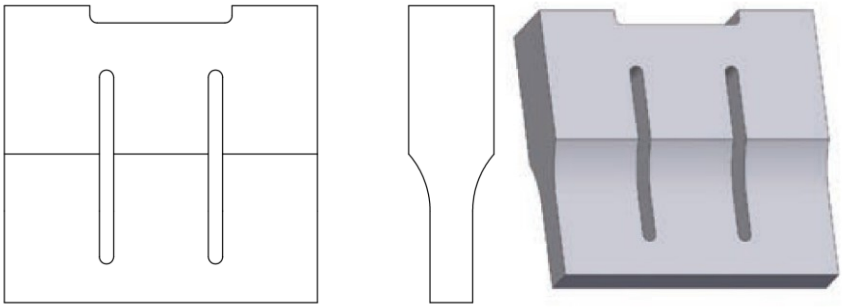


Figure 6. Horn OF-74419 (Emerson [Referred 2023b]).

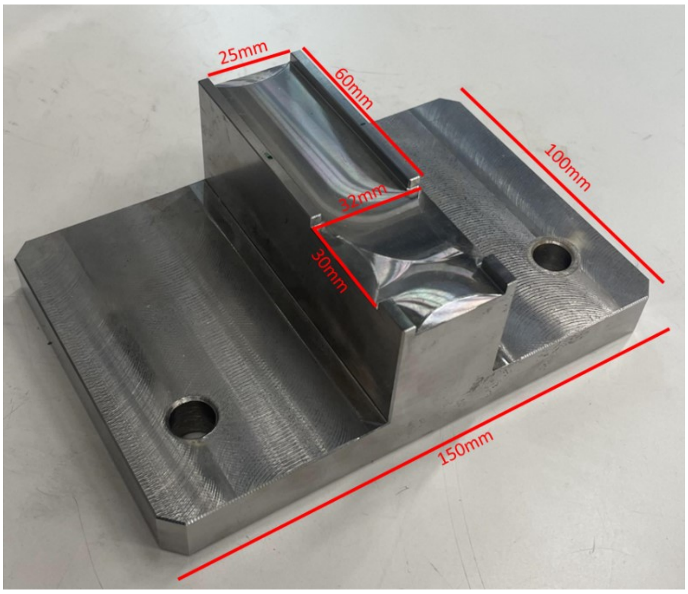



Figure 7. Custom anvil machined from stainless steel

The welding process was straightforward for the most part. Following ASTM F88, two samples, each cut to dimensions of 25x76 mm are sealed together based on the given parameter (ASTM F88 2015, p. 3). The width cannot be altered, but one can be lenient about the height of the sample. However, in the case of OPP+PE welding, the sample was too thin and it was slipping from the grip during the welding period. To solve this problem, Paper+PE was layered on top of it and below it to increase thickness (Figure 8).

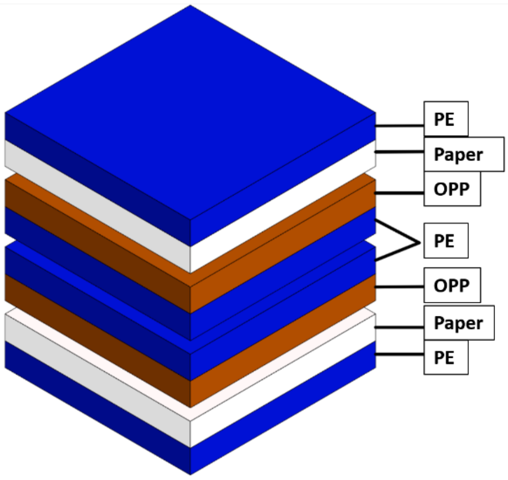



Figure 8. OPP+PE layered with Paper+PE

### 3.3.2 Ultrasonic Sealing parameters

The Branson 2000x ultrasonic machine has a multitude of parameters; however, only five parameters are suspected to be significant and will be tested. These parameters are weld time, hold time, pressure, trigger force, and amplitude.

Welding time is the period in which ultrasonic vibration is applied to the materials that are being joined. During that time, the ultrasonic energy propagates through the interface as well as through the whole material (STEFAN 2018). Proper selection of weld time is important since all of the weld happens in this period excluding 'afterburst'. High weld time may cause damage, deformation, or even burn to the material.

Hold time, or “consolidation time,” is the duration during which the horn holds its position to maintain pressure on the material after the weld time is over and the vibration stops. This facilitates the material interface to join properly during cooling time, thus increasing the seal strength and overall integrity of the weld (STEFAN 2018.)

The amplitude is the distance crossed by the horn within 1 cycle during the welding time. It determines the intensity of the mechanical vibration that is applied to the material and has a high influence on the final product because a higher amplitude generally corresponds with a higher energy transfer. (Stern [Referred 2023].)

Pressure is the force applied per area on the materials during ultrasonic welding. Proper pressure is imperative since it tolerates intimate contact between the materials, hence bringing about the necessary molecular intermingling for a strong bond. Insufficient pressures cause weak welds, while excessive pressures cause material deformation. (Dizu sonics [Referred 2023].)

Trigger force, also called “trigger threshold” or “activation force,” is the lowest weld-activating force. When this trigger force occurs, it activates the ultrasonic vibrations and other welding parameters. A properly selected trigger force ensures that accidental or premature initiation of the weld does not take place and assures consistency in many aspects of ultrasonic welding.

At first, preliminary testing was done to set the boundaries of the experiment. (see table below)

Table 3. Preliminary test input

<table>
<tr><td>Parameter</td><td colspan="12">Boundaries</td></tr>
<tr><td>Weld time (s)</td><td colspan="4">0.5</td><td colspan="4">1</td><td colspan="4">2</td></tr>
<tr><td>Hold time (s)</td><td colspan="4">0</td><td colspan="4">0.5</td><td colspan="4">1</td></tr>
<tr><td>Amplitude</td><td colspan="4">50%</td><td colspan="4">75%</td><td colspan="4">100%</td></tr>
<tr><td>Pressure (bar)</td><td colspan="3">2</td><td colspan="3">3</td><td colspan="3">4</td><td colspan="3">5</td></tr>
<tr><td>Trigger force (N)</td><td colspan="12">50-850</td></tr>
</table>

Pressure above 5 bar was not tested due to the ultrasonic sealer’s power supply reaching power overload. The required power supply is decided by several parameters; most of them were not altered by us. However, the parameters found to have activated the power overload alarm were weld time, afterburst, amplitude, pressure, and material type. The same problem occurred with weld time and afterburst; if their combination was high enough, then power overload would trigger. The trigger force was set at 850N since it had no significant impact on the seal's performance.

### 3.3.3 Seal strength test

Seal integrity is important in a multitude of industries like pharmaceuticals, cosmetics, and food processing, among others. Testing seal strength in a standardized fashion is essential to meet qualifications or attract potential customers.

In this study, SHIMADZU Autograph AGS-X 1kN universal testing machine was used to carry out seal strength tests on the three types of samples, which were Paper+PE, OPP+PE, and dispersion coated paper. Designed by SHIMADZU, this universal testing machine is highly flexible due to its modularity which is the ability to be attached with different types of jigs suitable for both compression and tensile test. (Shimadzu [Referred 2023a].) The model used for this sealing test can withstand a load of up to 10 kilonewtons; however, other models of the same series can handle up to 300 kilonewtons.

Figure 9. SHIMADZU Autograph AGS-X 1kN (Shimadzu [Referred 2023b]).

The experimental procedure was conducted in accordance with the ASTM F88 standard. SHIMADZU tensile machine AGS-X with 1kN load cell was used in this experiment. The test samples were prepared as per the ASTM F88. Samples were carefully attached to the SHIMADZU clamps using one tail-holding technique, which is to clamp each leg of the sample using a plastic clamp system (Figure 10) with a pneumatic switch. This was done to eliminate slippage and guarantee constant and uniform load application throughout the testing period. The initial grip separation distance was calibrated to 25 mm. The specimen was ensured to be centered laterally to the clamp during testing. One end of the sample was held still while the other end was slowly lifted until a 2% break-detection occurred. The force-displacement measurement begins recording, and the samples are peeled at a constant speed (300 mm/min) by the machine. Proper calibration was carried out before each batch test to guarantee correct and accurate results.

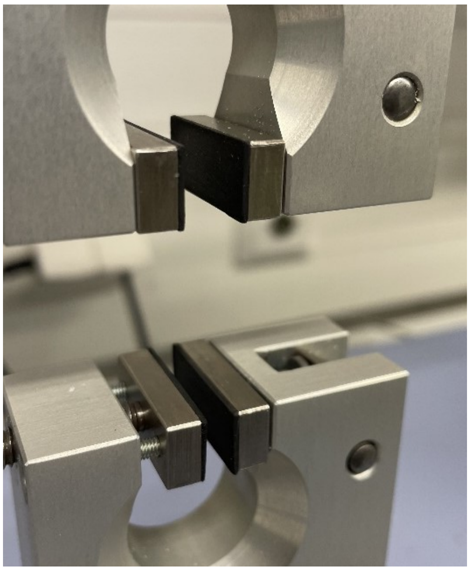


Figure 10. Clamp

TRAPEZIUM X software was used to control, monitor, and store the test results. The calibration of SHIMADZU is initiated within the control software. The test is automatically arranged by the software into patches and groups. The output of the test is a real-time graph of the displacement-force detected (Figure 11). From that graph, the software calculates the following: max force, force mean force, first force (first peak), and mean force(all).

However, the one mainly inspected is the maximum force since it indicates the smallest force required to peal the seal; in other words, Max force is detected.

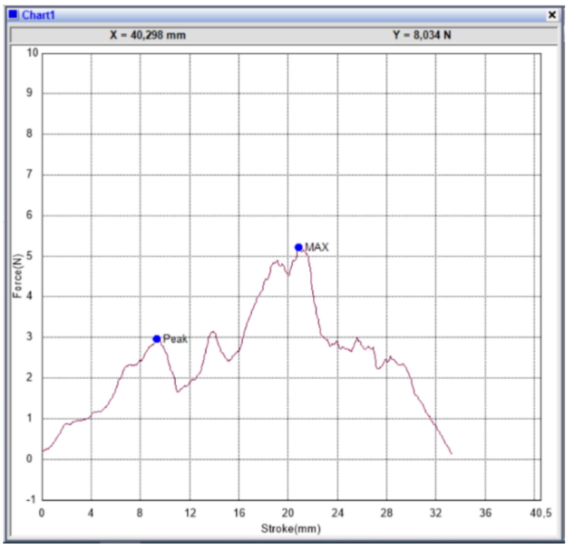



Figure 11. Force-displacement graph

### 3.3.4 Cup sealing

The second task was to use the same 3 materials as a lid and seal it on a disposable paperboard cup using an ultrasonic sealer. After that, a leak test is performed on it as per ASTM F3039 (2015).

The cups used were made from PE-coated paperboard and were pre-manufactured in the same lab. Its walls are made from a single blank that is ultrasonically sealed together. Cup dimensions are shown in Figure 12.

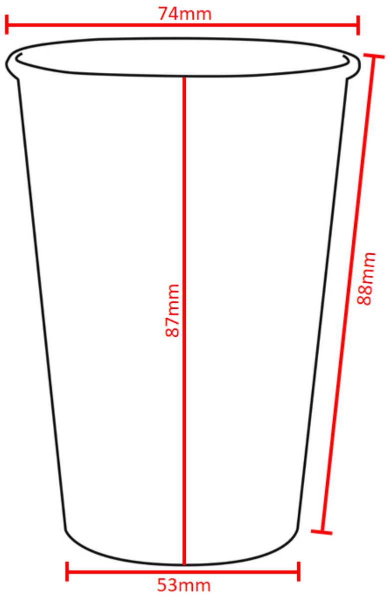



Figure 12. Disposable Cup dimension

For the sealing process of the cup, the same ultrasonic machine was used, but with a different type of anvil and horn. The horn used came with Branson 2000x and is called OF-74420 (Figure 13). The anvil used is nr-25930, a 3D printed metal designed by Branson (Figure 14). Its design allows for a 45-degree tilt, facilitating easy insertion and removal of cups without obstruction by the horn.


Figure 13. Horn OF-74420

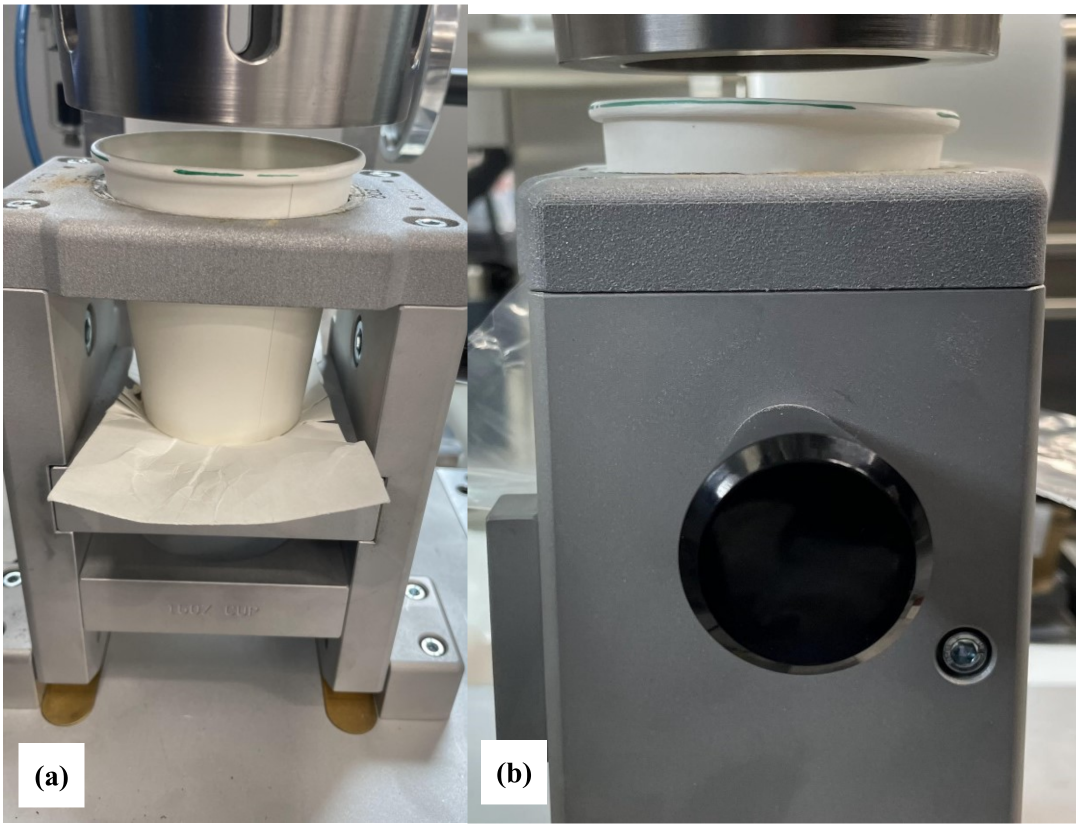



Figure 14. Cup anvil nr-25930 (a) front view (b) side view

Due to the force enacted by the horn on the cup, it gets stuck to the anvil; therefore, two different methods were used to remove the cup (Figure 15). The reason behind experimenting with different methods and their results will be discussed in detail in the following chapter.


Figure 15. Cup removal. (a) thick material used. (b) thin material used.

### 3.3.5 Leak test

The leak test was performed in accordance with a modified ASTM F3039 (2015). After sealing the cup with the lid, the cup was injected with 2 ml of a dye water solution using a syringe. The solution consists of water and 0.05% blue V sodium salt. This substance was used instead of ethanol because dispersion coated papers do not tolerate ethanol very well. After that, the cup was flipped so that the solution reaches the rim and the lid, where the leak was tested (Figure 16). After that, a timer was set, and a picture of the lid was taken every 10-20 seconds until multiple leaks occur.

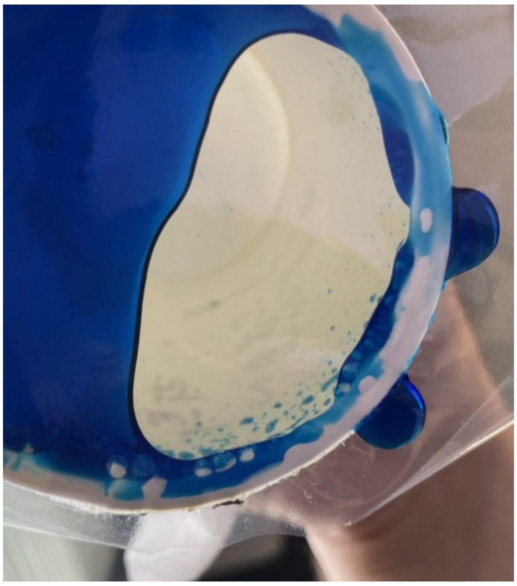


Figure 16. Bottom view of a flipped cup with dye water spreading

In this research, the seam of the cup is not considered for leak testing as it depends on the manufacturing method of the cup itself. Furthermore, regardless of the method used to seal the lid, the seam always remained the weakest link (Figure 17).

Figure 17. Illustration of cup seam failure

# 4 Results and discussion

The following chapter presents the results of both tests—seal strength and leak testing. Furthermore, it discusses the outcomes by analyzing the results and attempting to provide a proper explanation for the observed phenomena.

## 4.1 Seal strength results and analysis

The following are the results of Paper+PE seal strength compared with dispersion coated paper.

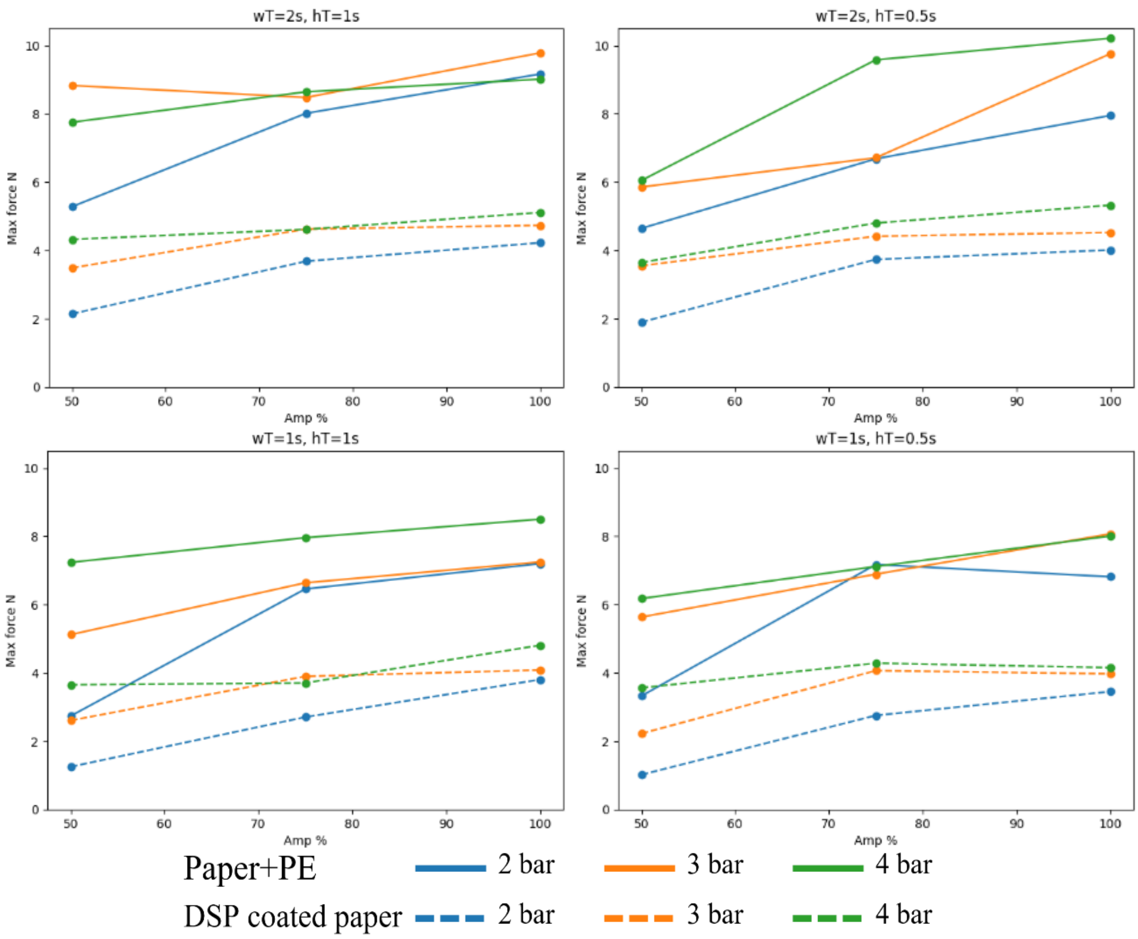



Figure 18. Seal strength test of Paper+PE and dispersion coated paper

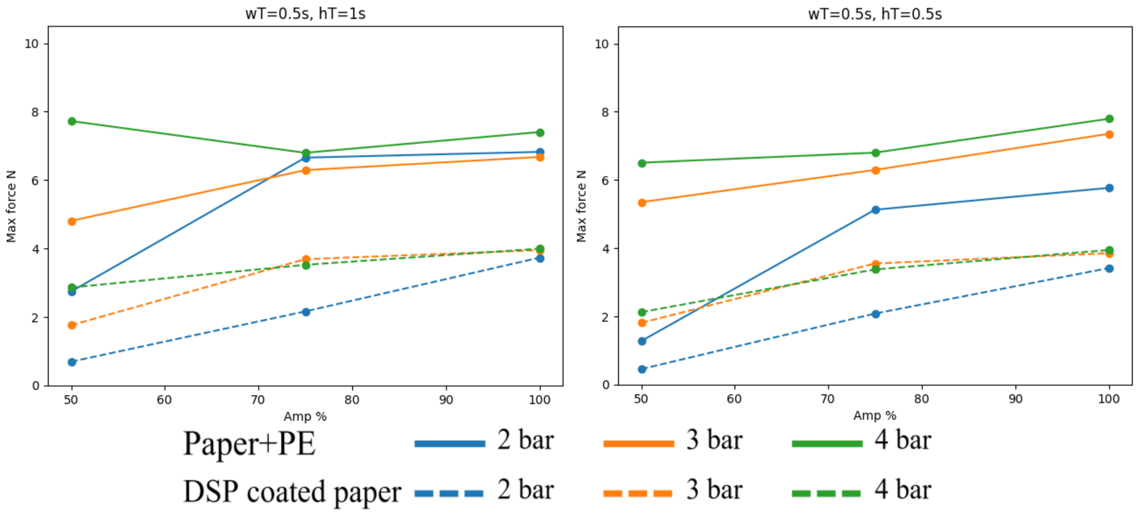



Figure 18 continues. Seal strength test of Paper+PE and dispersion coated paper

The following Table 4 below highlights the maximum seal strength achieved with each material along with the parameters used:

Table 4. Highest achieved seal strength

| Material | Max seal strength* | wT | hT | Amp | pressure |
|---|---|---|---|---|---|
| Paper+PE | 10N | 2s | 0.5s | 100% | 4 bar |
| Dispersion coated paper | 5.3N | 2s | 0.5s | 100% | 4 bar |
| OPP+PE | 50N | 2s | 0.8s | 100% | 3 bar |

*Displayed seal strength of OPP+PE is not the maximum possible value but is only used as a reference to show the magnitude of the difference

Upon analyzing the graph, a number of details were noticed:

The first noticeable finding from the graph is that seal strength was directly proportional to the increase of the four main welding parameters: welding time (wT), holding time (hT), amplitude, and pressure. The impact of hold time on seal strength diminishes as it increases, as observed in the plot. The difference between hT 0 and hT 0.5 is notable, whereas the contrast between hT 0.5 and hT 1 is less pronounced. This can be understood from an analytical standpoint. During hold time, the welder is not excited and the only activity that is going on is from the sample which is cooling/stabilizing, and the interface starts solidifying to form stronger bonds while the pressure is distributed equally. There is an upper limit to how long it takes for the sample to solidify; holding the pressure any longer yields indifference.

Dispersion coated paper graph showed a similar pattern as Paper+PE, with the exception that the seal strength was about half of Paper+PE. Additionally, ultrasonic sealing machines have power limits, and reaching power overload is dictated by the combination of multiple parameters, including welding time, pressure, amplitude, and afterburst. In the case of welding time, increasing it higher than 2 seconds was not possible because power overload occurred for any number bigger than that. A pressure of 6 bars was not possible because of power overload; even with 5 bars, it stopped due to overload on a couple of occasions.

No sign of burns was observed during the test, even when power overload was triggered. This is indicative that higher seal strength may be achievable by increasing pressure and weld time if a welding machine with a bigger power supply is used.

A regression analysis was done on the result to find the predictive value using analysis of variance. The p-values are higher than the threshold which is 0.15; this means that all these four variables contribute to changing the output (Table 5).

Table 5. predictive value of welding parameters

| | p-value |
|---|---|
| hT | 0.023 |
| wT | 6.4E-08 |
| Pressure | 3.4E-09 |
| Amp | 2.2E-12 |

## 4.2 Findings from seal strength test

Both Paper+PE and dispersion coated paper managed to weld. In the preliminary test, the trigger force was tested at values of 50 N, 200 N, 500 N, and 850N; and it showed no significant difference in seal strength. 50 N and 850 N were respectively the lower and upper limits of the ultrasonic sealer. Because of that, a constant value of 850N was opted for, which remained consistent throughout the tests.

### 4.2.1 Paper-Based Material's Seal Strength

The performances of Paper+PE and dispersion coated paper were relatively low compared to OPP+PE (Table 4). Paper+PE was singled out to investigate the cause of this.

At first, the possibility was considered that due to gravity, the PE side melts into the paper side instead of acting as an adhesive. To confirm the hypothesis, the following combinations were tested: Paper+PE – OPP+PE (Figure 19). However, there was no significant performance increase to prove my hypothesis.

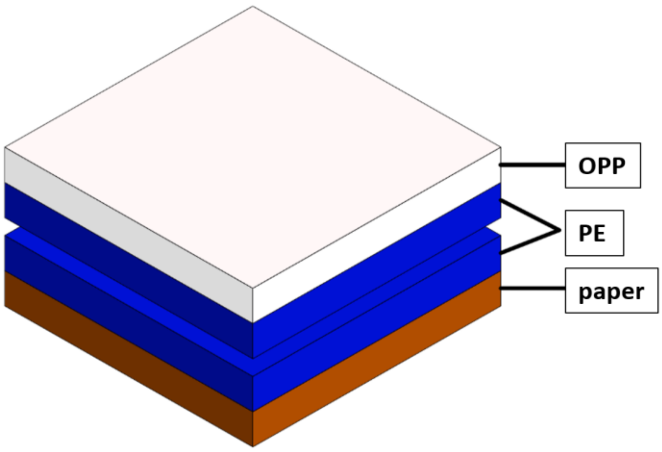



Figure 19. Sealing OPP+PE with Paper+PE

Furthermore, the tensile strength of both materials themselves was checked in case it was lower than the seal strength that was aimed for. The seal strength of Paper+PE was 85N, and OPP+PE was 50N; this is a high enough value to rule out this possibility. Furthermore, a tensile strength test was conducted on a single strip that had undergone ultrasonic welding. This was done to confirm whether the US process itself damages the material. However, the tensile strength exhibited no statistically significant differences (Table 6).

Table 6. Tensile strength of OPP+PE and Paper+PE (This table is only used to show the magnitude of the strength, more testing would be required for exact and reproducible value)

| | | |
|---|---|---|
| Raw | OPP+PE | 50N |
| | Paper+PE | 85N |
| Damaged | OPP+PE | 81N |
| | Paper+PE | 81N |

There were two other phenomena that were suspected but could not be verified properly:

- Delamination: the problem could be that the PE side delaminates from the paper even though it welds properly. This can be evident from the visual inspection of the peeled paper in Figure 20. Visual inspection shows that the weakest link is not the adhesive but the connection between the paper and PE. It could be that the tendency for delamination occurs due to damage caused by the welding process.

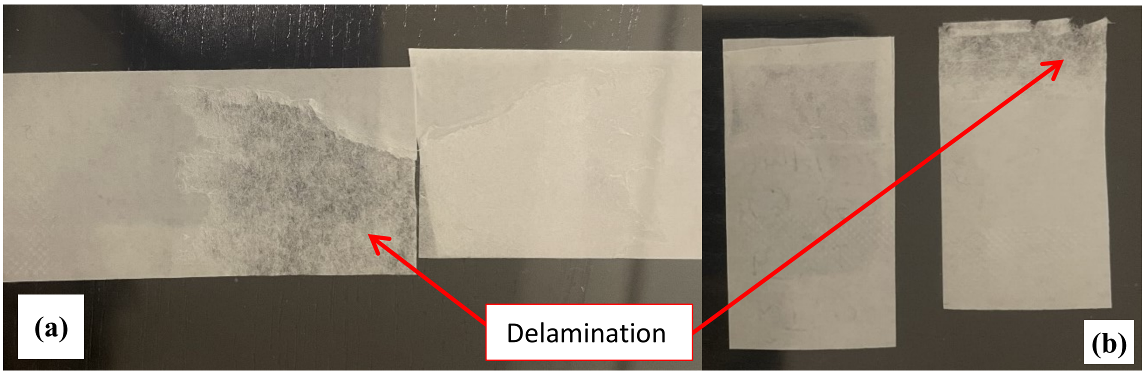



Figure 20. Peeled samples of (a) Paper+PE (b) Dispersion coated paper

- Not enough PE: the problem could be that the PE layer is simply too small to create a proper weld. The difference between 21% and 70% is large enough to not disqualify this possibility Table 7.

The relatively poor performance compared to OPP+PE could be the result of both mentioned problems instead of just one of them. Or it could be related to the nature of ultrasonic sealing.

Table 7. Thickness comparison

| Material | PE thickness | Percentage of PE thickness |
|---|---|---|
| Paper+PE | 15µm | 21% |
| OPP+PE | 35 µm | 70% |

### 4.2.2 Frequency and resonance

Welding OPP+PE directly did not yield a successful result. It often slipped from the anvil-horn grip; even when it did not slip, it did not seal fully. It is seal strength was around 2N which is extremely low.

In an attempt to stabilize it, a layer of Paper+PE was added as seen in Figure 21. This increased the sealing strength tremendously, so high that it did not peel but instead, the material broke (Figure 22). The reported seal strength is 50N which is the tensile strength of the material itself Table 6. This means that the actual seal strength surpassed the material tensile strength. To ensure that the performance increase was not from the PE leaking from Paper+PE to OPP+PE, the layers were arranged so that the paper side of Paper+PE touches the OPP+PE.

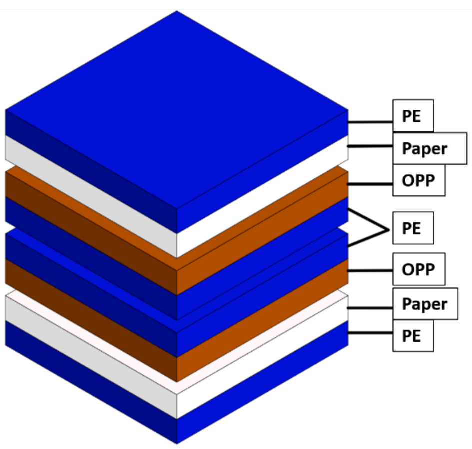



Figure 21. OPP+PE layering

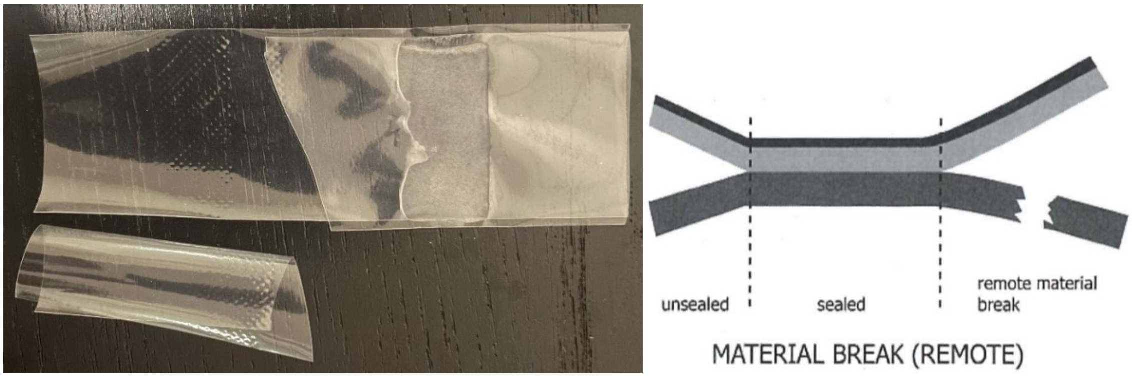



Figure 22. OPP+PE failure type: material break (ASTM International 2015, p. 5).

Our conclusion is that this occurred due to a phenomenon called resonance. In the context of US, resonance is a phenomenon that happens when the frequency of US machine matches the natural frequency of the welded object. Resonance is a factor that significantly affects the efficiency of vibration transfer through the body. The frequency of US usually cannot be changed or at least continuously. In the case of Branson 2000x, it was fixed at 20kHz. However, the natural frequency of the sample can be altered by thickening the welded object. A similar test was done in Charlier et al. (2021) paper.

Another possibility, which is less likely to be the case, is that the anomaly happens due to the conversion of vibration into heat before reaching the interface, resulting in the weld being evenly distributed. If this hypothesis is correct, it would mean that it acts like a heat sealer and does not utilize the benefits of the ultrasonic sealer.

Thickening the material to increase performance did not work with Paper+PE nor dispersion coated paper. However, the reason for this is unclear. Instead, the material starts burning, even though the material did not burn when welded normally even at the highest possible parameters (Figure 23).

Figure 23. Paper+PE burned due to thickness increase

## 4.3 Cup leak test

### 4.3.1 Sample test

In the course of the conducted leak test, a subset of the cups failed to establish a proper seal, and others, while sealed, exhibited leakage before the designated threshold time of 60 seconds. It should be noted that all nine images showcased in Figures 24, 25, and 26 feature cups that successfully achieved a seal without any leakage before the stipulated 60-second threshold. However, a consistent observation among the depicted cups is the occurrence of failure at the seam.

Certain images highlight cups with a pierced hole -further discussed in Section 4.3.2-. Cups sealed in this manner demonstrated a notably tight seal from the inside, preventing the lid from absorbing as much liquid as observed in instances with a higher pressure difference, consequently resulting in heightened integrity.

Analysis of the Dispersion Coated Paper testings revealed that any pressure below 2 bars failed to facilitate a proper seal, while pressures surpassing 3 bars caused the cup to adhere to the anvil, resulting in surface damage. Although employing a weld time of 1.5 seconds successfully sealed the cup, it fell short of achieving leakproof status within the defined threshold.

In contrast to dispersion Coated Paper, the Paper+PE material (Figure 26) required less pressure to achieve a proper seal. However, pressures below 0.5 bars and welding times below 1 second proved insufficient for a complete seal. Remarkably, for the Paper+PE material, hole piercing was mandatory to ensure a successful seal.

The following is the top view of the cup leak test. The cup is made from PE-coated paperboard. The lidding materials used are OPP+PE, Paper+PE, and dispersion coated paper.

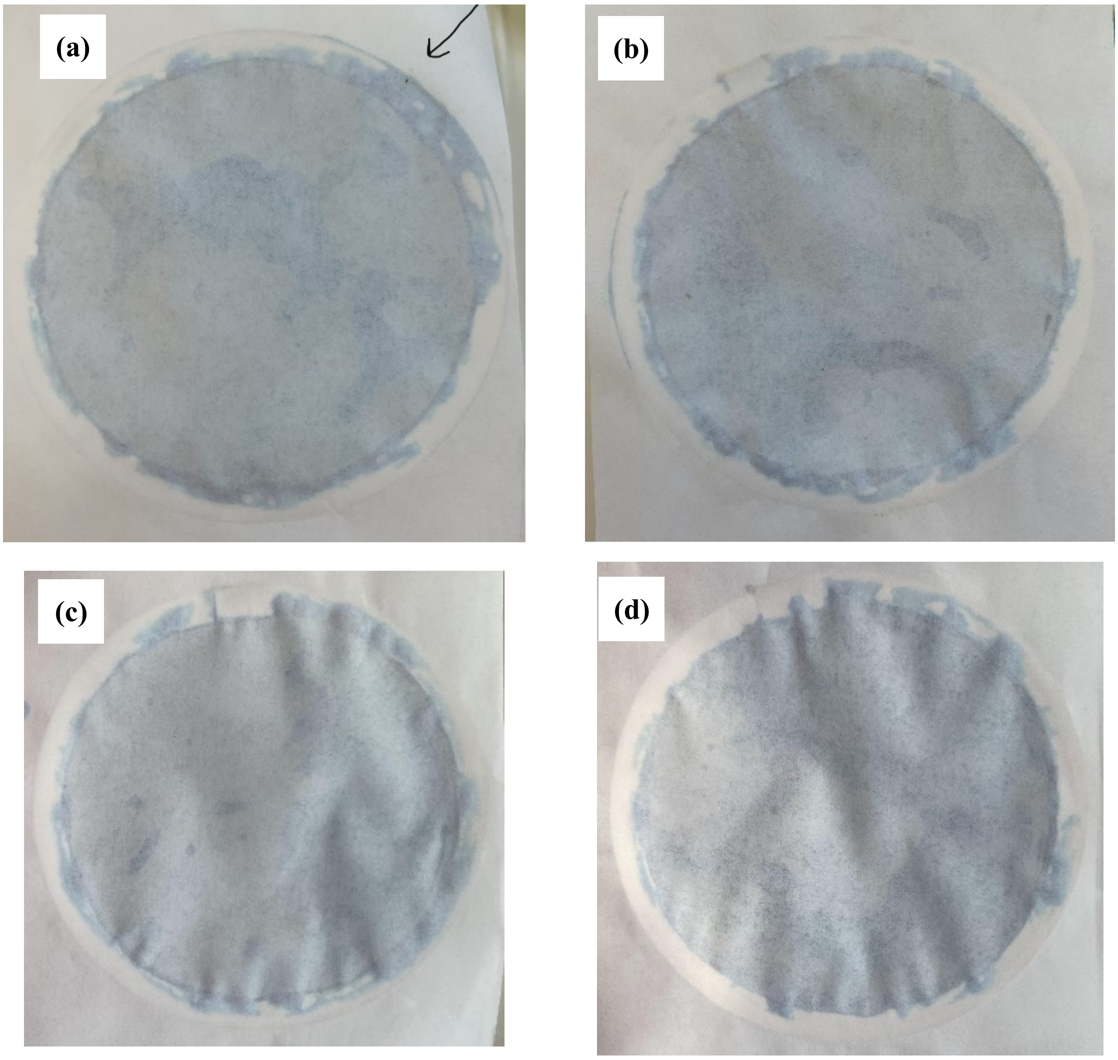



Figure 24. 1 minute after the leak test started on paper cups sealed with dispersion coated paper as a lid. Sealing properties are in of order wT, hT, amp, pressure: (a) 3s,2s,100%,2bar (b) 2.5s,2s,100%,2bar (c) 2s,2s,100%,2bar (d) 2s,2s,100%,2bar. All 4 except (d) have pierced hole

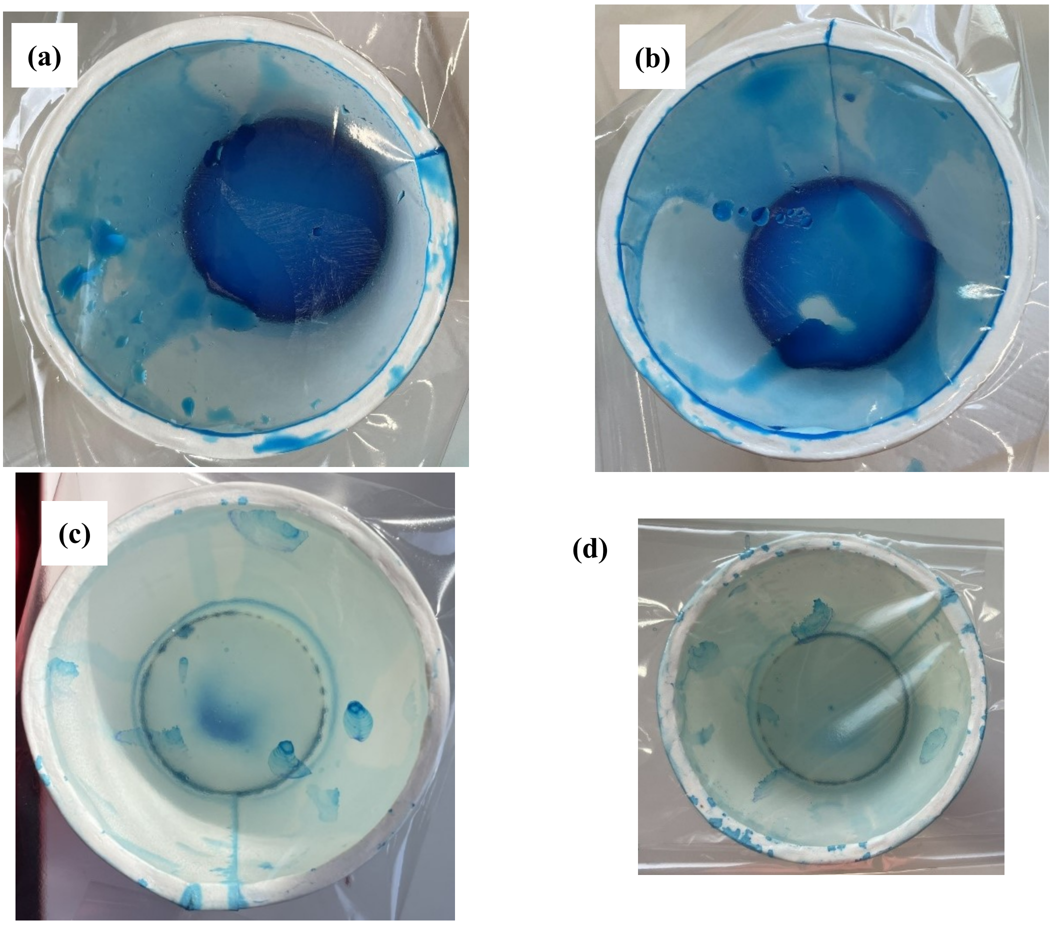



Figure 25. 1 minute after the leak test started on paper cups sealed with OPP+PE as a lid. Sealing properties are in of order wT, hT, amp, pressure: (a) 2s,1.5s,100%,0.5bar (b) 1.5s,3s,100%,0.5bar (c) 2s,2s,100%,0.5 bar (d) 2s,2s,100%,0.5bar. All 4 except (d) have pierced hole

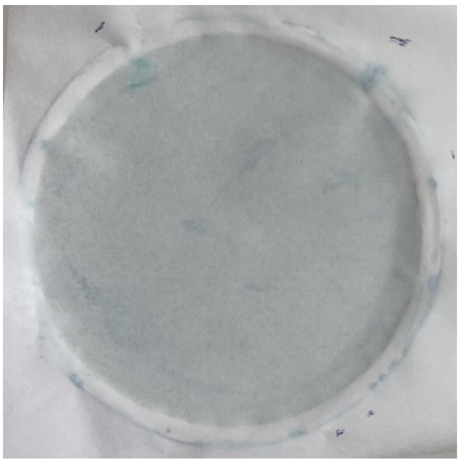


Figure 26. 1 minute after the leak test started on paper cups sealed with Paper+PE as a lid. Sealing properties are in of order wT, hT, amp, pressure: 2s,2s,100%,0.5bar

### 4.3.2 Hole piercing

A recurring issue observed was excessive leakage from the cup lid. Further investigations revealed that it was caused by a pressure difference between the inside of the cup and the ambient environment. To temporarily address this issue, a hole was pierced in the cup's wall. This was conducted for experimental purposes and is not intended for industrial use.

More info on the reasoning for piercing a hole will be given in section 4.4.2. The displayed results in figure 24 and figure 25 are samples from cups with and without a pierced hole.

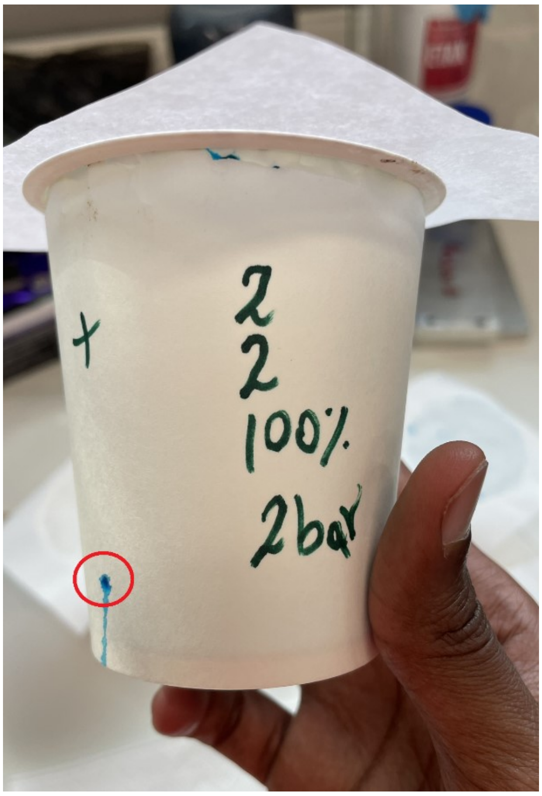



Figure 27. Cup with pierced hole marked red

## 4.4 Cup failure analysis

### 4.4.1 Wall Compression

Cup wall compression happens when there is a space between the rim and the anvil. Due to the force from the horn, the upper part of the cup wall gets slightly squished down giving wrinkles to it (Figure 28). These heavy wrinkles become a reason for the liquid to be absorbed by the walls of the cup (Figure 29). The most probable cause is that the inner PE coating for the cup, which acts as a barrier against liquid, gets damaged because of the heavy wrinkles.

Figure 28. Compressed cup wall

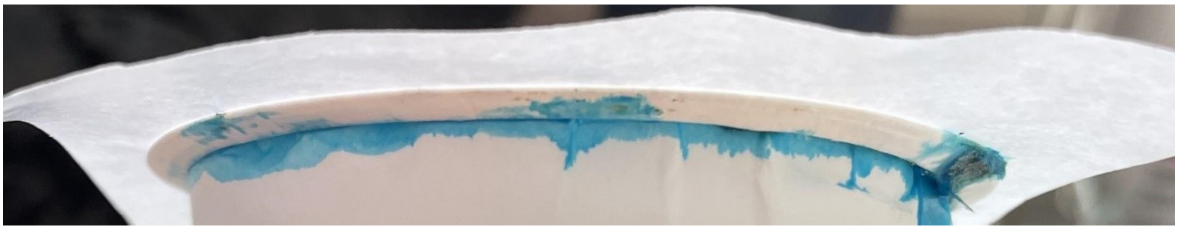


Figure 29. Liquid absorbed by cup wall

The extra space between the rim and the anvil was caused by the sheet of paper put between the cup and the anvil, which was put there to assist the removal of the cup from the anvil when it gets stuck. The material initially used was paper, and switching to thinner material like plastic solved the issue (Figure 15). This issue is unlikely to be encountered in a commercial setting because there are a multitude of ways to solve this problem. However, the observed phenomenon is intriguing enough to warrant mention here.

### 4.4.2 Pressure difference

An issue noticed while sealing the cups was that the lid starts to protrude upward during the welding time (Figure 30). This protrusion prompted the lid to have crumbles which acted as a catalyst for leakage during the leak test. To continue the test in finding an acceptable welding parameter without dealing with this problem directly, a solution was implemented. Prior to welding, a small hole was created in the cup wall before welding it (Figure 27); this makes the pressure inside the cup similar to the ambient pressure and the lid stays flat. With this simple modification, the seal performed greater during the leak test, and the ranges of sealing parameters in which the cup could be sealed without leakage happening before the threshold has increased. It is important to acknowledge that this was carried out solely for experimental purposes. In an industrial application, a non-destructive solution will be required.

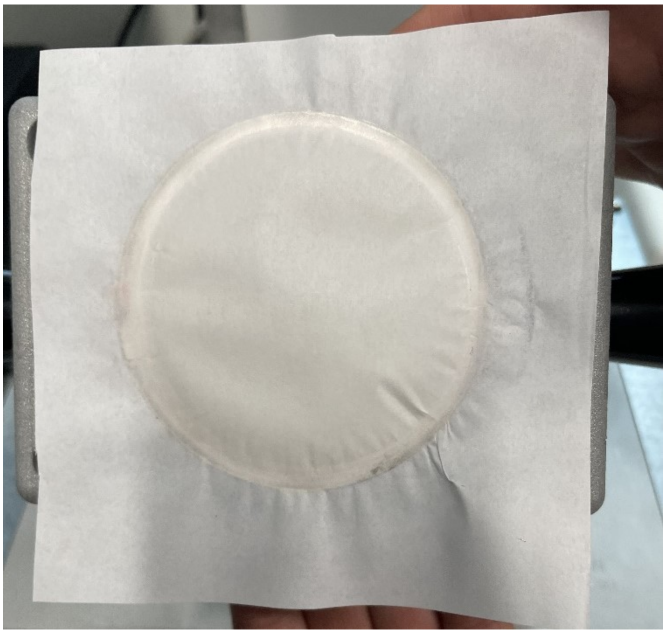


Figure 30. Lid protruding

### 4.4.3 Rim Compression and Flattening

The testing cups had rounded rims and the ultrasonic sealer used has a high minimum trigger force of 44N; due to that the welding does not initiate on contact of the horn to the lid, but instead, it activates when the horn pushes the lid down and flattens the rounded rim along the anvil.

This flattening of the rounded rim crumples the lid. Similar to the previous issue, those crumbled spots become likely spots for leakage; however, it is not as detrimental as lid protrusion during welding. One solution to this problem was to use the ultrasonic sealer to pre-flatten the rim cup using a low weld time. This was done to flatten the rim without burning or damaging it (Figure 31). After this, the sealing commences and the lid will have no crumbles nor any visible inconsistencies; thus, decreasing the leak tendency.

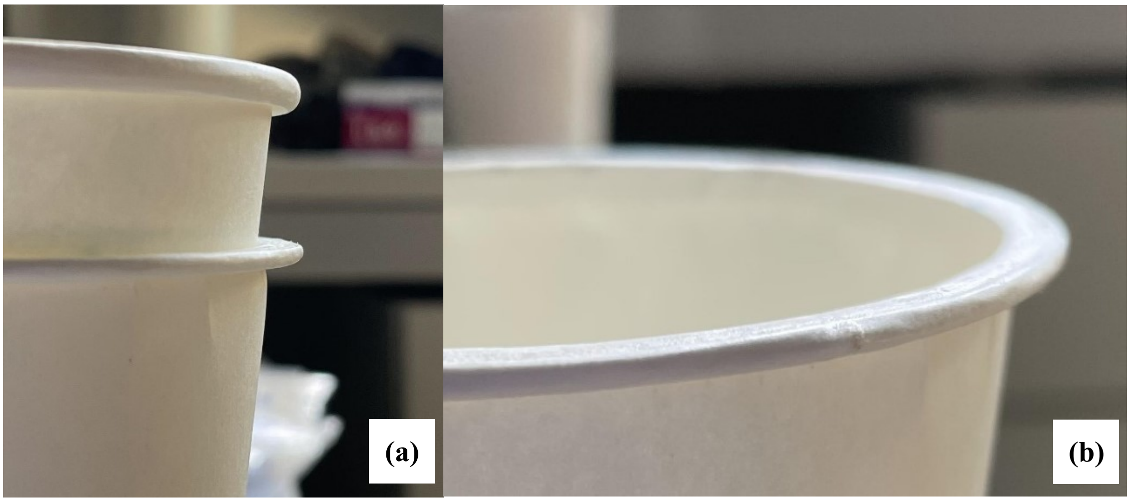



Figure 31. (a) round rim (top), flattened comparison (bottom) (b) flattened rim

### 4.4.4 Understanding Rim Damage and Material Absorption

On some occasions, the rim starts absorbing the liquid during leak testing, and this happens regardless of the integrity of the seal. However, liquid absorption was not a problem when the rim was not pre-flattened. This could mean that the issue is similar to the wall compression and that the PE coating gets damaged. Further investigation would be required to determine the exact cause.

Our experiments and findings conclude that flexible fiber-based materials can be used as lidding materials for disposable cups. In the results, Examples of sealable parameters for different materials were provided, and the types of failures encountered during the research were discussed. Explanations of the underlying causes were also offered.

Over the period of the research, workarounds and solutions to some of the problems discussed in this chapter were found. In the next chapter, potential improvements that could be done on the cup, the sealer, and the sealing process will be discussed.

# 5 Suggestions for potential improvements

## 5.1 Cup anvil

In section 4.4.1, the study demonstrated the detrimental effect of cup wall compression. To reduce the space between the rim and the anvil, having a proper ejector is important.

The primary role of the anvil is to help with the transmission of the acoustic vibration. Therefore, in this situation, contact between the anvil and the cup wall is unnecessary. An alternative solution is to use an anvil with a clearance fit. The interface getting sealed is the cup rim, not the cup wall. Therefore, having an anvil which is in contact with the cup wall is unnecessary, especially when it complicates the removal process. The anvil used which was nr-25930 required a slight push-down for the cup rim to properly sit on the anvil. This indicates the anvil is not a clearance fit.

## 5.1 Pressure difference

The negative effects of sealing lids with uneven surfaces or crumbled parts have been shown in section 4.4.2. The cause of it was high pressure inside the cup relative to ambient pressure during welding time. The proposal is the addition of an extra step in the manufacturing process that reduces the gas content inside the cup right before sealing. The exact mechanism that causes the pressure increase is unknown to the author. Therefore, there might be a more appropriate solution than adding an unnecessary extra step, especially a step which may interfere with Modified Atmosphere Packaging (MAP).

## 5.2 Cup rim

Designing drinking disposable cups with a round rim is logical since round rims are human-friendly. However, in this case, it becomes redundant as the rim gets squished by the ultrasonic sealer regardless of the setting. It is also suspected that it slightly contributes to the lid having wrinkles, ultimately increasing the likelihood of leakage. Therefore, cups with flat rims should be opted for. machines. An untested alternative solution is to employ ultrasonic machines in which the trigger force can be set low enough to detect the lid upon contact.

# 6 Conclusions

The thesis had two parts. The first part was to test the seal strength of flexible fiber-based materials and thermoplastics that are sealed using an ultrasonic sealing method. The second part was to use the same materials as lidding material for disposable paper cups sealed using an ultrasonic sealer.

The objective was reached, and the research was successful, answering the majority of the research questions. All three materials (OPP+PE, Paper+PE, dispersion coated paper) welded successfully and reached acceptable seal strength, showing good results in leak tests when used as lidding material. This is not to say there were no challenges and inconveniences. For instance, OPP+PE frequently slipped when the welding process starts; the cup was getting stuck in the anvil; there was a rise of pressure inside the cup when welded, causing the lid to protrude and increasing the likelihood of leakage; in some instances, the cup started absorbing the leak testing liquid and started delaminating. However, all of these and many more problems were solved or found workarounds, and the research was successfully carried out.

The reference material OPP+PE seal strength resulted in 50N; however, the other two, Paper+PE and dispersion coated paper seal strengths, were significantly lower maxing at 10N and 5.3N respectively. The significant difference in seal strength was expected since Paper+PE and dispersion coated paper are paper-based with a plastic component making up only about 12% of the total thickness, as compared to 100% plastic in the case of OPP+PE.

It is completely possible to reach values higher than that if an ultrasonic sealer with higher power output is used. This is because the seal strength of both materials kept increasing with the usage of higher parameters and showed no sign of reaching the global maximum, nor did they show any sign of deterioration like burning.

The cup's leak test showed good results too, with the exception of constant failure at the side seam. The seam failure was expected and ignored since it depends on the cup design, not the lid sealing method or the parameters used. However, the rest of the lid showed clean results and no leakage. Although the sealing window was small.

Common failures included: the lid not sealing fully in the first place, the lid sealing fully but leaking before the target time was reached, and finally the cup rim getting stuck to the anvil when high pressure is used.

Of course, every phenomenon encountered could not be explained, meaning there is room for further research. These phenomena include:

- Why increasing the thickness of Paper+PE and dispersion coated paper does not increase its seal strength similar to how it increased for OPP+PE?
- Why does the pressure inside the cup increase relative to the ambient pressure during the sealing process?
- What is the exact type of damage that happens to the cup's PE-coating that subsequently causes it to absorb liquid?

Throughout the period of this research, a number of ways that the process could be improved were found, ranging from the material type, machine used, process, and procedure. Some of these suggestions included: the usage of materials with thicker PE; using a machine with higher power output, lower trigger force, and modifiable frequency; proper cup ejector; and finally changing the rounded cup rim to a flat rim.

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Appendix 1. Python code used for generating the seal strength plot

```
import matplotlib.pyplot as plt

# Data
data1 = [
    #//
    [0.5,0,50,2,1.18605333333333],
    [0.5,0,75,2,5.59113],
    [0.5,0,100,2,7.42686],
    [0.5,0,50,3,4.43744666666667],
    [0.5,0,75,3,5.38052666666667],
    [0.5,0,100,3,5.32754333333333],
    [0.5,0,50,4,6.57797],
    [0.5,0,75,4,6.1901],
    [0.5,0,100,4,7.00521666666667],
    [0.5,0.5,50,2,1.27805],
    [0.5,0.5,75,2,5.12801],
    [0.5,0.5,100,2,5.76826],
    [0.5,0.5,50,3,5.35006333333333],
    [0.5,0.5,75,3,6.29564],
    [0.5,0.5,100,3,7.35371],
    [0.5,0.5,50,4,6.50681333333333],
    [0.5,0.5,75,4,6.80165],
    [0.5,0.5,100,4,7.79398],
    [0.5,1,50,2,2.74600333333333],
    [0.5,1,75,2,6.65680333333333],
    [0.5,1,100,2,6.82501],
    [0.5,1,50,3,4.81075666666667],
    [0.5,1,75,3,6.29119],
    [0.5,1,100,3,6.67676],
    [0.5,1,50,4,7.7254],
    [0.5,1,75,4,6.79775],
    [0.5,1,100,4,7.40334],
    [1,0,50,2,2.76163],
    [1,0,75,2,3.48433],
    [1,0,100,2,7.68415],
    [1,0,50,3,6.38906],
    [1,0,75,3,7.66585],
    [1,0,100,3,7.00911],
    [1,0,50,4,6.804438],
    [1,0,75,4,6.603656],
    [1,0,100,4,6.70232],
    [1,0.5,50,2,3.3269725],
    [1,0.5,75,2,7.17576],
    [1,0.5,100,2,6.818335],
    [1,0.5,50,3,5.638916],
```

```
    [1,0.5,75,3,6.89337],
    [1,0.5,100,3,8.073712],
    [1,0.5,50,4,6.18],
    [1,0.5,75,4,7.1182675],
    [1,0.5,100,4,8.01055],
    [1,1,50,2,2.742196],
    [1,1,75,2,6.46039],
    [1,1,100,2,7.202088],
    [1,1,50,3,5.1237325],
    [1,1,75,3,6.6407],
    [1,1,100,3,7.25035],
    [1,1,50,4,7.2397825],
    [1,1,75,4,7.96265],
    [1,1,100,4,8.5033975],
    [2,0.5,50,2,4.648525],
    [2,0.5,75,2,6.68442],
    [2,0.5,100,2,7.953485],
    [2,0.5,50,3,5.858895],
    [2,0.5,75,3,6.71482333333333],
    [2,0.5,100,3,9.75863666666667],
    [2,0.5,50,4,6.050745],
    [2,0.5,75,4,9.58295],
    [2,0.5,100,4,10.2143733333333],
    [2,1,50,2,5.283675],
    [2,1,75,2,8.01695666666667],
    [2,1,100,2,9.166665],
    [2,1,50,3,8.83251],
    [2,1,75,3,8.48113333333333],
    [2,1,100,3,9.78534],
    [2,1,50,4,7.756235],
    [2,1,75,4,8.64664666666667],
    [2,1,100,4,9.01630333333333],

    #//
]

data2 = [
    #//
    [0.5,0,50,2,1.12387],
    [0.5,0,75,2,2.03872],
    [0.5,0,100,2,2.623],
    [0.5,0,50,3,1.91013],
    [0.5,0,75,3,3.22306],
    [0.5,0,100,3,3.44122],
    [0.5,0,50,4,1.69647],
    [0.5,0,75,4,2.96124],
    [0.5,0,100,4,3.95147],
    [0.5,0.5,50,2,0.45542],
```

```
[0.5,0.5,75,2,2.08406],
[0.5,0.5,100,2,3.41706],
[0.5,0.5,50,3,1.81151],
[0.5,0.5,75,3,3.5516],
[0.5,0.5,100,3,3.85495],
[0.5,0.5,50,4,2.12693],
[0.5,0.5,75,4,3.37772],
[0.5,0.5,100,4,3.94805],
[0.5,1,50,2,0.69571],
[0.5,1,75,2,2.16464],
[0.5,1,100,2,3.73439],
[0.5,1,50,3,1.761],
[0.5,1,75,3,3.69044],
[0.5,1,100,3,3.95246],
[0.5,1,50,4,2.86432],
[0.5,1,75,4,3.52546],
[0.5,1,100,4,3.99749],
[1,0,50,2,2.043935],
[1,0,75,2,3.21308],
[1,0,100,2,4.38222],
[1,0,50,3,3.09728],
[1,0,75,3,4.09714],
[1,0,100,3,4.297],
[1,0,50,4,3.75029],
[1,0,75,4,4.6802],
[1,0,100,4,4.54303],
[1,0.5,50,2,1.02095],
[1,0.5,75,2,2.75823],
[1,0.5,100,2,3.45572],
[1,0.5,50,3,2.22711],
[1,0.5,75,3,4.06969],
[1,0.5,100,3,3.97635],
[1,0.5,50,4,3.56619],
[1,0.5,75,4,4.28753],
[1,0.5,100,4,4.15842],
[1,1,50,2,1.25456],
[1,1,75,2,2.70955],
[1,1,100,2,3.80667],
[1,1,50,3,2.61092],
[1,1,75,3,3.90152],
[1,1,100,3,4.08757],
[1,1,50,4,3.65595],
[1,1,75,4,3.70817],
[1,1,100,4,4.81165],
[2,0.5,50,2,1.90123],
[2,0.5,75,2,3.7398],
[2,0.5,100,2,4.01457],
[2,0.5,50,3,3.55331],
```

```
    [2,0.5,75,3,4.41806],
    [2,0.5,100,3,4.52718],
    [2,0.5,50,4,3.64888],
    [2,0.5,75,4,4.80461],
    [2,0.5,100,4,5.32731],
    [2,1,50,2,2.14476],
    [2,1,75,2,3.6854],
    [2,1,100,2,4.22602],
    [2,1,50,3,3.49106],
    [2,1,75,3,4.62781],
    [2,1,100,3,4.73693],
    [2,1,50,4,4.32579],
    [2,1,75,4,4.61897],
    [2,1,100,4,5.11388]

    #//
]

# Array of desired hT and wT combinations
combinations = [(0, 0.5)]

# Get the default color cycle from Matplotlib's rcParams
default_color_cycle = mpl.rcParams['axes.prop_cycle']

# Convert the color cycle to a list for easier access
color_cycle_list = list(default_color_cycle)

# Define your x and y values
x_values = [1, 2, 3, 4, 5]
y_values = [2, 3, 4, 5, 6]

# Define your color_map with default colors from the color cycle
color_map = {
    2: color_cycle_list[0]['color'],
    3: color_cycle_list[1]['color'],
    4: color_cycle_list[2]['color'],
    # Add more values and corresponding colors as needed
}

# Create a figure and axis
fig, ax = plt.subplots()

# Iterate through the data and use colors from color_map or default colors
for i, val in enumerate(x_values):
    if val in color_map:
        color = color_map[val]
    else:
        color = color_cycle_list[i % len(color_cycle_list)]['color']
```

```
    ax.plot(val, y_values[i], marker='o', linestyle='-', label=f'Data Point
{i+1}', color=color)

#---------
# Plotting

for ht, wt in combinations:
    plt.figure()

    # Filter data for the current hT and wT combination for data1
    filtered_data1 = [(amp, max_force, pressure) for wT, hT, amp, pressure,
max_force in data1 if hT == ht and wT == wt]

    # Filter data for the current hT and wT combination for data2
    filtered_data2 = [(amp, max_force, pressure) for wT, hT, amp, pressure,
max_force in data2 if hT == ht and wT == wt]

    # Separate X and Y values for each pressure value for data1
    pressure_values = sorted(set(d[2] for d in filtered_data1))
    for pressure in pressure_values:
        x_values = [amp for amp, _, p in filtered_data1 if p == pressure]
        y_values = [max_force for _, max_force, p in filtered_data1 if p ==
pressure]

        color = color_map.get(pressure, 'black')
        plt.plot(x_values, y_values, marker='o', linestyle='-',
label=f'data1: {pressure} Bar', color=color)

    # Separate X and Y values for each pressure value for data2
    pressure_values = sorted(set(d[2] for d in filtered_data2))
    for pressure in pressure_values:
        x_values = [amp for amp, _, p in filtered_data2 if p == pressure]
        y_values = [max_force for _, max_force, p in filtered_data2 if p ==
pressure]

        # Plotting separate line for each pressure value for data2 (dotted
line)
        plt.plot(x_values, y_values, marker='o', linestyle='--',
label=f'data2: {pressure} Bar')

    plt.title(f"wT={wt}s, hT={ht}s")
    plt.xlabel('Amp %')
    plt.ylabel('Max force N')
    #plt.legend()

    plt.ylim(0, 10.5)
    plt.tight_layout(pad=0.2)
    plt.show()
```