Creating Easy Peel Longitudinal Seals in a Mono-PP Film without Additives in the Sealant Layer using Ultrasonic Sealing on a HFFS System

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Abstract: Current trends show that mono-material films are replacing complicated multi-material films in the packaging industry. These mono-material films are more suitable for recycling. However, achieving the same functionalities like easy pealing and sufficient barrier properties is a challenge. This research investigates two topics, namely the creation of an easy peel seal and damage to the barrier layer while sealing mono-materials with the ultrasonic sealing process.

This research is executed by creating mono-PP (BOPP-PP-EVOH-PP) packages on an Omori HFFS system with an ultrasonic longitudinal seal and conduction transverse seal. The speed of the machine was set to 80 packs/minute. The longitudinal seal was created with a 35kHz Herrmann Ultraschall LSM with the amplitude ranging from 70 – 100% and the pressure from 0,1 – 2,3 bar.

The seal strengths are measured using the KOPP Labormaster HCT 3000. The results confirm that it is possible to create an easy peel seal with ultrasonic sealing with material where no controlled contamination has been applied in the sealant layer. An explanation is found in the heat generation of ultrasonic sealing.

Cross-sections of seals have been investigated using the Keyence VHX 7000 digital microscope. It is found that the barrier layer might be disrupted while sealing a mono-material with ultrasonic sealing.

Keywords: Ultrasonic sealing, conduction sealing, easy peel seal

1 Introduction

The European Commission has set a goal to ensure that all plastic packaging in 2030 is either reusable or can be recycled cost-effectively [1]. In that sense, the European Commission encourages economic growth while minimizing environmental impact [2].

When trying to minimize the environmental impact of a product, certain actions have more impact than others. One source states the order of importance as follows: reuse, reduce and recycle, recover and dispose with reuse having the most impact and dispose having the least [3]. The source referred to is The Circular Economy for Flexible Packaging (CEFLEX) which is a European collaboration of organizations, associations and companies involved in flexible packaging. Another source presents a more extensive overview the next order of actions: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover, reconcentrate and redistribute with refuse having the highest impact and redistribute the least [4]. What they agree on and what is good to note, is that there are steps that probably can have more impact than recycling as action, although of lot of attention is going towards recycling as the publication of many recycle guidelines underline, like those of Recyclass and CEFLEX [3, 5].

1.1 Mono-materials

One way to reduce the environmental impact of a packaging system is to increase its recyclability. This can be achieved by using mono-materials instead of multi-materials. ‘Mono’ means one or single [6], so a mono-material literally means ‘one material’.

Mono-materials have the potential to have a high recyclability performance [2, 3, 7-9]. The main reason for this is that mono-materials do not require material separation of the packaging system during the sorting [2, 10].

Carullo, Casson [7] state that these mono-materials seem to be a valid replacement for multi-materials. They show in a life cycle assessment (LCA) that mono-materials consistently show a lower impact on the environment than multi-materials. This is confirmed by research from TNO [11]. An important condition is that a large enough portion is collected, sorted and recycled.

However, when looking at the overall environmental impact of a consumer good, there should be a balance between sufficient functionality, to ensure the quality and safety of the product throughout its shelf life, and material that can effectively be recycled. A mono-material might include other layers to achieve the required functionality regarding light, oxygen, other gases, microorganisms and moisture barriers. From an industrial point of view related to the recycling process, a mono-material may contain a maximum of 5% other materials than the core polymer of the material and that the added materials do not disrupt the recycling process [8, 11].

1.2 Regulatory stimulation towards mono-materials

There are some regulations in place to stimulate the use of mono-materials rather than multi-materials. The Dutch governmental body, for example, offers subsidies for changing production processes to be suitable for easier-to-recycle materials [8]. Furthermore, the Dutch Packaging Waste Foundation (Afvalfonds verpakkingen [12]) executing the Extended Producer Responsibility schemes, gives discounts to recyclable packaging to stimulate the use of materials that are easier to recycle.

1.3 Challenge: sealing

A challenge that arises with the implementation of mono-materials, is the sealing. Conduction sealing with direct contact between the sealing tools and the materials to be sealed, is the most used sealing process, and usually, a packaging system that is sealed with conduction sealing, consists of a film with a heat-resistant outer layer and a sealant layer with a low seal initiation temperature [13]. The difference in melting temperature between these two layers should be high enough to allow for a workable temperature sealing window. The sealant layer should be sealed at this temperature without melting the outer layer. Since the material type of both layers is the same for mono-materials, the difference in melting temperature cannot be as high as is possible with dissimilar materials [9]. Conduction sealing can include temperature fluctuation of 10°C, which can often not be handled by the small sealing window associated with mono-materials at high production speeds [14, 15]. Another heat sealing technology that is often used in practice is ultrasonic sealing [16]. This paper will examine both conduction and ultrasonic sealing methods for the sealing of mono-materials on horizontal form-fill-seal machines.

1.4 Conduction sealing

Conduction sealing is a relatively simple process. Two heated sealing jaws apply pressure and heat to two films. The heat and pressure will make the polymer chains diffuse and entangle, which will bond the two films at the seal interface [13, 17]. A simplified representation of this process can be found in Figure 1.

The parameters that mainly influence this process, are sealing temperature, pressure and dwell time (sealing time) [18]. Inherent to this process is that the seal interface has a lower temperature than the sealing jaws. The longer the dwell time, the lower this temperature difference has to be [17, 19, 20].

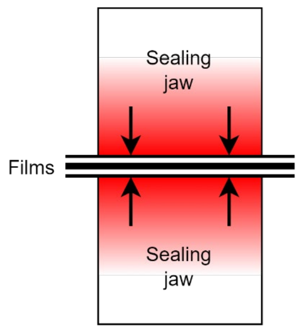

Figure 1: Simplified representation of the conduction sealing process

1.5 Ultrasonic sealing

Another sealing method is ultrasonic sealing. Within this sealing process, electrical energy is converted into heat energy through ultrasonic mechanical waves. The heat is generated at the seal interface and causes the sealant layers to merge [21]. Ultrasonic sealing generates the heat that is necessary for sealing using friction [22]. Intermolecular and interfacial friction between the layers are responsible for the sealing of the layers [19, 23-26].

The mechanical waves have a certain frequency and amplitude which together with the dwell time and sealing force (pressure), form the main parameters influencing this process [19, 23, 27]. To find the optimum seal settings, usually the amplitude and the sealing force are variated since the frequency and dwell time are usually set.

The process starts with electrical energy that is used as an input. From this input, a high-frequency electrical oscillation is created. A *converter* can convert these electrical oscillations into mechanical ones. This converter typically uses piezoelectric transducers to do so. Piezoelectric transducers use the inverse piezoelectric effect to convert a high-frequency electrical signal into a high-frequency mechanical vibration [28]. At the converter a mechanical oscillation is created with a certain frequency (oscillations per second) and a certain amplitude (the peak height compared with a reference value). This amplitude is transformed by a mechanical booster. Connected to the booster is the horn. This horn transforms the amplitude and passes the oscillations onto the substrate. Behind the substrate (the to-be-sealed films) there is an anvil [19, 29]. A simplified representation of this process can be seen in Figure 2.

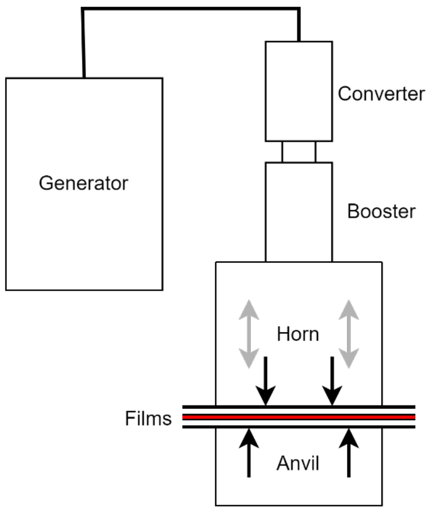

Figure 2: Simplified representation of the ultrasonic sealing process

This process can be applied to most thermoplastics and some nonferrous metals, such as aluminum, nickel, brass and copper [27]. It can effectively seal mono-materials due to its heating principle [30], the heat is formed only at the contact surface of the two films and not at the contact surface between sealing bar and material.

To compare conduction and ultrasonic sealing, it is useful to look at the pictures made with a Fluke heat camera in Figure 3. These pictures clearly show the excessive heat around the conduction sealing jaws and the local heat generation for the ultrasonic sealing process.

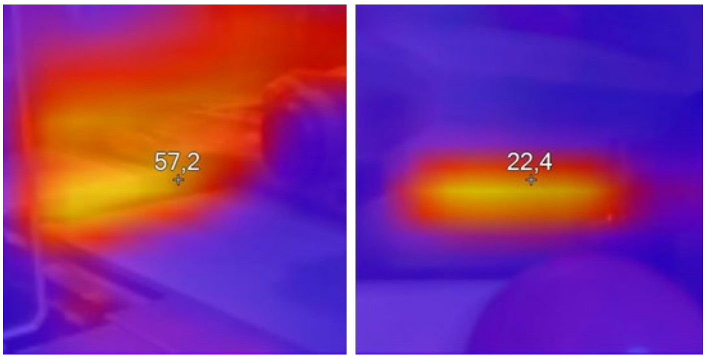

Figure 3: Photos of running conduction sealing (left) and ultrasonic sealing (right) with a Fluke heat camera

2. Easy peel

Seal strength is the force required to pull apart a seal [31]. Based on this seal strength, two general seal types can be distinguished: a lock seal and a (easy) peel seal [32]. The difference between the two types is that the peel seal is easier to open for consumers than the lock seal.

A type of peel seal called 'easy peel seal' is a seal that can be opened manually and does not require any tools, like scissors or a knife. The easy peel seal can be opened with constant force within the range of what humans normally can apply and without destroying the package [33, 34].

The easy peel seal is seen as a major advantage for the consumer [31] and therefore is applied in a broad range of products [24]. If a seal is designed to be easy to open, it will show low seal strengths [13, 35]. It should be noted that a seal should have a certain minimum seal strength to survive throughout the supply chain. For most packaging applications there is an operating window in which there is a right balance between the seal strength and the openability of the seal [31].

To make the easy peel quantifiable, Sängerlaub, Reichert [33] defined a seal as an easy peel if the peeling force is less than 15 to 20N/15mm. They differentiate different kinds of (easy) peel seals in their research, namely: soft peel (1-6N/15mm), easy peel (6-10 N/15mm), peel (10-20 N/15mm) and strong peel (>20 N/15mm). The strong seal is not seen as an easy peel, since the packaging material is destroyed when the seal is opened.

2.1 Creation

Generally, easy peel seals can be created using one of the following techniques: controlled contamination, dissimilar resins and controlled delamination [32, 36]. Controlled contamination adds an incompatible polymer to the sealant layer. These polymers will create so-called 'islands' in the sealant area, preventing a strong seal from being formed. Dissimilar resins seals two different materials that together cannot form a strong seal. Controlled delamination seals the sealant layers that initially form a lock seal. The sealant layer can be detached (delaminated) from the next inner layer [31, 33, 36]. The advantage of this technique is that sealing conditions don't affect the peeling force [33].

2.2 Easy peel through controlled contamination

Usually, an easy peel seal is created using the controlled contamination technique. An incompatible polymer is introduced in the sealant layer, which leads to weak intermolecular bonds. Due to the difference in crystallization temperatures and surface energy, small islands are formed within the sealant layer while cooling. This decreases the seal strength, thereby making the seal easier to open [33]. An example of a contaminant that can be used in a LDPE sealant layer, is PB [24].

There are some limitations associated with the controlled contamination easy peel technique. First, a film with a controlled contamination peel mechanism is less affordable than the same film without these contaminants [24, 31]. Thus, the sealant layer (which includes the peel components) must be kept as thin as possible [24]. Secondly, a film with controlled contamination needs to be thicker than a film without [31]. Thirdly, the easy peel films realized with controlled contamination are sensitive during processing, because of the small sealing window. If the seal settings are too high for example, a lock seal can be created [31].

In controlled contamination, additional material is introduced in the sealant layer. One could think this would have a negative impact on the recycling of that specific film since multi-material films are difficult to recycle [37]. For the common combination of a polyethylene (PE) sealant layer and a polybutylene (PB) contamination, the PB has a neglectable influence on recycling. This is based on the information offered by KIDV [8]. They state that a package must consist of PE for more than 90% for it to be considered ‘optimal’ for recycling. The contamination that is introduced into the sealant layer inherently decreases the PE fraction, but as long as the contamination does not cause the PE fraction to decrease below 90%, the film with controlled contamination is seen as ‘optimal’ for recycling.

3 Research question

During testing with mono-materials in combination with ultrasonic sealing at the company Omori Europe, a surprising result was that it was possible to realize an easy peel seal with ultrasonic sealing on a material that was not made for easy peeling. This is confirmed by an ultrasonic sealing technology supplier [38]. This paper tests whether this is indeed possible and will speculate on the cause of this. The research question that will be answered is formulated as follows:

> Is it possible to create an easy peel seal with ultrasonic sealing technology on a flexible mono-PP packaging film without controlled contamination?

4 Method

To answer the research questions an ultrasonic longitudinal seal and a conduction transverse seal have been realized on an Omori bellpack machine with a Herrmann Ultraschall LSM unit. The anvil incorporated into the ultrasonic sealing system has four lines in its geometry.

The packages are created with different seal settings of the ultrasonic seal. Different combinations of pressure; varying from 0.1 to 2.3 bar; and amplitude; varying between 70 and 100%; have been used. Material BOPP / PP-EVOH-PP (20/30µm) has been used. This material does not include a controlled contamination easy peel mechanism and is considered a mono-material (less than 5% of the weight is EVOH and more than 90% of the weight is PP [8]).

4.1 Tests

To evaluate the seal performance, the seal strength and seal integrity are required [18]. The seal strength refers to the force it takes to open a certain seal. To determine the peeling behavior of the consumer, the seal strength after cooling should be considered. The seal integrity refers to the leak tightness that a package has [13]. This can be evaluated with methods like dye penetration [31, 39, 40] or the bubble test [31, 40-42].

T-Peel: The seal strength will be evaluated through T-peel tests and the seal integrity will be evaluated by performing dye penetration tests. The tests will be performed following ASTM standard F88. According to that standard, during the T-peel tests the maximum peeling force and the seal failure mode must be recorded [43]. The tests are executed with the KOPP Labormaster HCT 3000 (see Figure 4). Samples with a width of 25mm are cut from the created packages (speed = 200mm/min).

Figure 4: Labormaster HCT 3000 with the arrow indicating how the machine peels

An easy peel seal has a maximum seal strength of 10N/15mm according to Sängerlaub, Reichert [33]. The samples used for the testing had a width of 25mm, so they are considered to be an easy peel if they have a maximum seal strength of around 17N/25mm.

Dye leak detection: A dye penetration test will be executed with blue dye. If no leaks are observed, it can be concluded that no channels or leaks bigger than 50µm are present in the created seals [39].

Image analysis: To check the seal area of the samples, microscopic pictures will be taken. This is done with a Keyence VHX 7000 digital microscope. The samples are embedded in epoxy, which is hardened for at least 24 hours. Afterward, the samples are grinded and polished, to make sure that a clear picture will appear on the microscope. This is done with the Struers Tegramin-30 machine.

5 Results

A summary of the results of the T-peel and dye penetration tests is presented in Table 1. The dye penetration test is performed on a package produced with the lowest setting where the pressure was 0,1 bar and the amplitude 70%. This means that the ultrasonic generator is set on 70%. This package did not show leakages, as shown in Figure 5. It is expected that all packages produced with higher seal settings do not have leakages.

Figure 5: Dye penetration test with settings 0,1bar and 70%

Table 1: Overview of results from the T-peel and dye penetration tests

Pressure (bar)	Amplitude	Mean seal strength	Standard deviation	Sample size	Seal integrity
0,1	*70%*	19,6623	3,68984	*13*	*No leakage*
0,3	*80%*	22,3192	3,32326	*13*	*No leakage*
0,5	*80%*	19,9444	3,30858	*9*	*No leakage*
0,7	*80%*	22,6191	4,26963	*11*	*No leakage*
0,9	*80%*	22,8900	2,65022	*11*	*No leakage*
0,1	*100%*	26,3927	6,43537	*11*	*No leakage*
1,1	*100%*	24,7520	3,14134	*10*	*No leakage*
1,1	*70%*	16,9025	4,35664	*8*	*No leakage*
1,3	*100%*	24,6720	3,22146	*10*	*No leakage*
1,5	*100%*	27,7964	4,19705	*14*	*No leakage*
1,7	*100%*	30,1723	4,34560	*13*	*No leakage*
1,9	*100%*	21,2027	3,80075	*11*	*No leakage*
2,1	*100%*	28,8443	4,92775	*14*	*No leakage*
2,3	*100%*	26,3392	2,31043	*12*	*No leakage*

A two-way ANOVA showed a significant ($p<0,05$) result of the amplitude on the seal strength. The interaction effect and the pressure showed to have an insignificant ($p>0,05$) influence on the seal strength.

In Figure 6 a scatter plot of all the T-peel test results is presented. In this figure, a horizontal line is placed at 17N/25mm. All measurements below the line are considered to be easy peel seals.

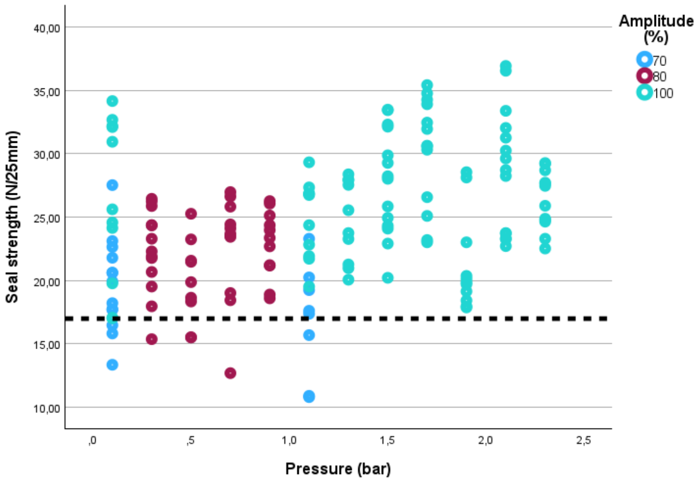

Figure 6: Scatter plot of all measurements with a line at 17N/25mm

From this figure it can be concluded that it indeed is possible to create an easy peel film, especially for lower pressures and amplitudes. However, most measurements are not considered easy peels. Note that the mean of the treatment with a pressure of 1,1 bar and an amplitude of 70% is even below 17N/25mm.

Based on these results, it seems possible to create easy peel seals with the ultrasonic sealing technology on materials that don't include a controlled contamination easy peel mechanism.

5.1 Imaging

A microscopic image of an ultrasonic seal created with an anvil with 4 stripes can be found in Figure 8. This figure clearly shows that ultrasonic sealing generates heat at the points of friction. Due to the geometry of the anvil, four sealing lines are realized. These four lines can be distinguished in the microscopic picture. In between these local sealing sites, it looks like there is an area that is not sealed. This observation is confirmed by the graph showing the peeling force throughout the time (Figure 7). This graph shows clear peaks and valleys with the seal strength at the valleys being close to zero.

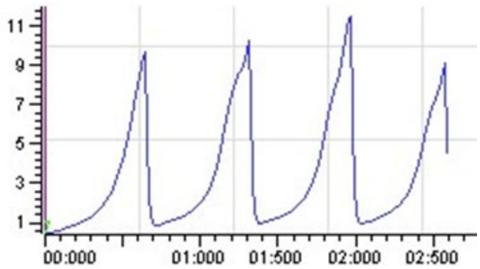

Figure 7: Graph showing the sealing force throughout the peeling time (withdrawal speed: 200mm/min; maximum seal strength: 12,00N/25mm) from the same sample as Figure 8

Figure 8: Cross section of an ultrasonic seal with four indents (OPE / PE-EVOH-PE (25/50) including controlled delamination easy peel with sealing settings 100% and 0,1bar)

It can be concluded that the outcome of the tests show that it is possible to create peelable seals with ultrasonic sealing.

5.2 Speculating

Speculations on why this is possible will be presented here. Ultrasonic sealing technology heats the materials from the inside, as can be seen with the local sealing sites in Figure 8. This figure shows that there is no continuous seal, but rather four local sealing sites. It is expected that the seal will be so easy to peel because there are just a few thin sealing sites that need to be peeled. It might very well be the case that the seal is considered to be easy to peel, because four very thin seals are peeled, instead of one wider one. Another possibility that explains why the peeling of this seal is considered to be easy is that delamination occurs at the four sealing sites. This way, the delamination must be initiated with some force, but the rest of the seal will peel easily if the adherence between the different layers is low. However, to draw conclusions on whether and why an easy peel seal can be created with ultrasonic sealing on materials that do not include an easy peel mechanism, more research is required.

5.3 Damage to the barrier layer

While looking at the microscopic images, it can be observed that the barrier layer seems to be disrupted at the local sealing sites produced with ultrasonic sealing. This can be observed in Figure 9. The pictures there show a non-continuous EVOH layer at the side of the indent in the seal. The pressure does not seem to affect the barrier layer disruption, as it is visible at 0,1 bar (low) and 2,3 bar (high).

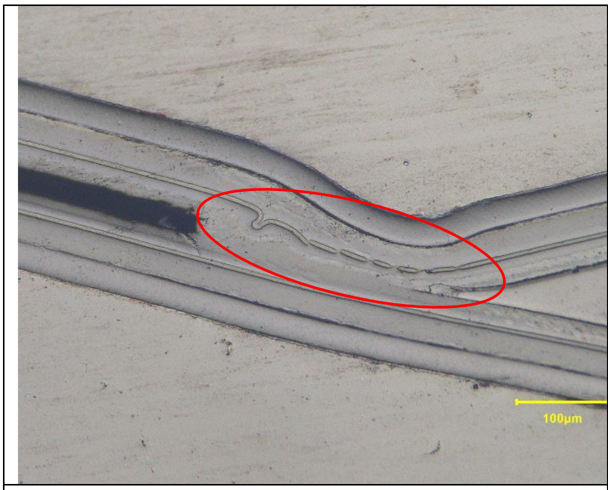	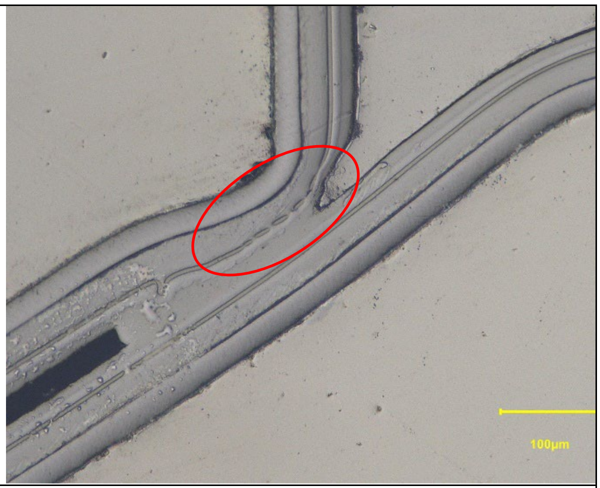
Setting: 0,1 bar and 100%	Settings: 2,3 bar and 100%

Figure 9: Microscopic images of material OPE/PE-EVOH-PE (25/50) including controlled delamination easy peel with sealing settings 100% and 0,1bar or 2,3bar to see the disruption of the EVOH layer

No clear source has been found in literature that addresses the possibility of this specific issue. In practice it has been found that it is possible to obtain a damaged EVOH layer due to too high sealing settings of the ultrasonic sealing process. It is confirmed in an interview with an ultrasonic seal expert that layers of a mono-material may be merged if the pressure of the ultrasonic sealer is too high [38]. This might cause damage to the EVOH layer.

As the oxygen seems to be able to travel through the layers without having to pass an EVOH layer based on Figure 9, it is expected that this observation will have an impact on the oxygen permeability of the seal. As the permeation of gases and vapors is one of the key parameters that determine the shelf life of a product and thus the performance of a packaging, the destruction of a barrier layer might be highly undesired and thus requires more research [7].

6 Limitations

This research includes some limitations. To start with, an assumption is made about the seal integrity of the seal with higher seal settings. This seems a valid assumption but still requires further testing to be certain. Another limitation is that delamination of the entire package was observed during the T-peel tests instead of the expected cohesive peel. An easy peel seal can be realized through controlled delamination, but this should not delaminate and thus damage the entire package. The last limitation of this research concerns mono-materials. They are often chosen because of their lower impact on the environment. However, the effect of recycling is only seen if at least 69% of the plastic is collected and sorted [11].

7 Future research

This research offers some directions for future research. The first direction regards the creation of an easy peel seal on the material without controlled contamination. At this moment, it is not fully understood why this is possible. For future research, it is suggested that an evaluation of the T-peel test is performed for this application. It might for example be the case that an ultrasonic and conduction seal that show the same maximum seal strength, show different peel experiences.

While looking at the microscopic images that have been created, a disruption of the EVOH layer can be observed. More research is required to see what the effect of these interruptions might be.

The effect of material, amplitude and pressure on the EVOH layer disruption could be analyzed by taking microscopic pictures of ultrasonic seals for different material, amplitude and pressure combinations.

The effect that these disruptions in the EVOH layer cause, might be evaluated by performing oxygen permeability tests with the seal area included in the sample. If the EVOH layer disruption is problematic, the oxygen permeability will be higher than expected. EVOH acts as the main barrier against oxygen within most mono-material films. It is not expected that the damage to the EVOH layer has a significant effect on the oxygen permeability since successful shelf life tests have been reported with oxygen-sensitive products packed in a mono-material with an EVOH layer with a conduction transverse seal and an ultrasonic longitudinal seal. However, testing is required to confirm this hypothesis.

8 Conclusion

From this research it can be concluded that it is possible to create an easy-peel seal with a mono-material film that does not include controlled contamination, using ultrasonic sealing technology. This phenomenon has not been reported for conduction sealing. It is expected that this is possible due to the heating mechanism of ultrasonic sealing. The heat is generated from within the film, and with a 4-lined anvil, it is possible to seal four local stripes, without sealing the area in between. Therefore, only four narrow seals need to be peeled, instead of one, like those created with conduction sealing.

Furthermore, ultrasonic sealing can cause disruption within the EVOH layer for normal sealing settings. What the effect of the disruption of the EVOH layer is, is not known. It might influence the barrier properties of the film. To get insight in this phenomenon, more research is needed.

Acknowledgements

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References

1. European Commission, *REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC*. 2022.

2. Nonclercq, A., *Mapping flexible packaging in a Circular Economy.* Final Report, 2016.

3. CEFLEX, *DESIGNING FOR A CIRCULAR ECONOMY*. 2023.

4. Bruijnes, C., et al., *The State of Sustainable Packaging*. 2020.

5. RecyClass. *RecyClass: the future of plastic is circular!* 2024; Available from: https://recyclass.eu/.

6. Cambridge Dictionary, *Mono*, in *Cambridge Dictionary* 2024.

7. Carullo, D., et al., *Testing a coated PE-based mono-material for food packaging applications: an in-depth performance comparison with conventional multi-layer configurations.* Food Packaging and Shelf Life, 2023. **39**: p. 101143.

8. KIDV, *Achtergronddocument KIDV Recyclecheck Flexibele Kunststof Verpakkingen 2023.* 2023.

9. Hauptmann, M., et al., *The effect of flexible sealing jaws on the tightness of pouches made from mono-polyolefin films and functional papers.* Packaging Technology and Science, 2021. **34**(3): p. 175-186.

10. Kaiser, K., M. Schmid, and M. Schlummer, *Recycling of polymer-based multilayer packaging: A review.* Recycling, 2017. **3**(1): p. 1.

11. Golkaram, M. and L. Heemskerk, *Comparative environmental life cycle assessment of PET/LDPE, MONO PET and MONO PE films.* 2022.

12. Afvalfonds verpakkingen, *Explanation Fee Modulation Plastic Packaging*. 2023.

13. Bamps, B., M. Buntinx, and R. Peeters, *Seal materials in flexible plastic food packaging: A review.* Packaging Technology and Science, 2023.

14. Eckhardt, K., *INTERVIEW WITH WATTTRON GMBH*, Easy Engineering, Editor. 2021.

15. Bach, S., *Information Digital sealing from company Watttron*, R. Waterham, Editor. 2024.

16. Nase, M., et al., *Fracture mechanics characterisation of peelfilms.* Deformation and Fracture Behaviour of Polymer Materials, 2017: p. 271-281.

17. Morris, B.A. and J.M. Scherer, *Modeling and experimental analysis of squeeze flow of sealant during hot bar sealing and methods of preventing squeeze-out.* Journal of Plastic Film & Sheeting, 2016. **32**(1): p. 34-55.

18. Najarzadeh, Z. and A. Ajji, *A novel approach toward the effect of seal process parameters on final seal strength and microstructure of LLDPE.* Journal of Adhesion Science and Technology, 2014. **28**(16): p. 1592-1609.

19. Bach, S., K. Thürling, and J.P. Majschak, *Ultrasonic sealing of flexible packaging films–principle and characteristics of an alternative sealing method.* Packaging Technology and Science, 2012. **25**(4): p. 233-248.

20. Tetsuya, T., et al., *The effect of heat sealing temperature on the properties of OPP/CPP heat seal. I. Mechanical properties.* Journal of applied polymer science, 2005. **97**(3): p. 753-760.

21. Snelson, T.T., *Ultrasonic Sealing of PEM Fuel Cell Membrane Electrode Assemblies*. 2011: Rensselaer Polytechnic Institute.

22. Bhudolia, S.K., et al., *Advances in ultrasonic welding of thermoplastic composites: A review.* Materials, 2020. **13**(6): p. 1284.

23. Yousefpour, A., M. Hojjati, and J.-P. Immarigeon, *Fusion bonding/welding of thermoplastic composites.* Journal of Thermoplastic composite materials, 2004. **17**(4): p. 303-341.

24. Nase, M., et al., *Ultrasonic sealing versus heat conductive sealing of polyethylene/polybutene-1 peel films.* Journal of applied polymer science, 2013. **130**(1): p. 383-393.

25. Hopmann, C., et al., *Determination of the frequency-and temperature-dependent stiffness and damping properties of thermoplastics for the prediction of the vibration and heating behaviour during ultrasonic welding.* Welding in the World, 2022. **67**(2): p. 435-445.

26. Mediana, M., *Flexible Packaging Challenges Met with Ultrasonic Sealing Solutions.* Plastics Engineering, 2018. **74**(2): p. 12-15.

27. Herrmann Ultraschall. *Ultrasonic welding*. 2023; Available from: https://www.herrmannultraschall.com/en/welding-using-ultrasonics/ultrasonic-welding#c1865.

28. Zhang, K., et al., *Review of the design of power ultrasonic generator for piezoelectric transducer.* Ultrasonics Sonochemistry, 2023: p. 106438.

29. Herrmann Ultraschalltechnik GmbH & Co. KG, *Installation instruction translation Ultrasonic weld module ULTRAPACK digital 35/06.06 with LSM G1 Fin 35*, H.U.G.C. KG, Editor. 2023.

30. Herrmann Ultraschall. *Ultrasonic sealing: Enabling Sustainability*. 2020; Available from: https://www.herrmannultraschall.com/en/company/news-events/news-detail/enabling-sustainability.

31. Dudbridge, M., *Handbook of seal integrity in the food industry.* 2016.

32. Ilhan, I., et al., *Understanding the factors affecting the seal integrity in heat sealed flexible food packages: A review.* Packaging technology and science, 2021. **34**(6): p. 321-337.

33. Sängerlaub, S., et al., *Identification of polybutene-1 (PB-1) in easy peel polymer structures.* Polymer Testing, 2018. **65**: p. 142-149.

34. Ernst, U., *Peelable seam systems and their production.* Packaging Technology and Science, 1994. **7**(1): p. 39-50.

35. Hendrickson, M., *Analysis of Diffusion in Heat Seals Using Energy Dispersive X-ray Spectroscopy.* 2015.

36. Brandenburg, J.S., *Packaging design: Functions and materials*, in *Controlled and Modified Atmospheres for Fresh and Fresh-Cut Produce*. 2020, Elsevier. p. 185-210.

37. Pettersen, M.K., et al., *Recyclable mono materials for packaging of fresh chicken fillets: New design for recycling in circular economy.* Packaging Technology and Science, 2020. **33**(11): p. 485-498.

38. Pasker, H., *Practical information on ultrasonic sealing from Herrmann Ultraschall*, R. Waterham, Editor. 2023.

39. Moghimi, N. and S.-i. Park, *Leakage assessment of flexible pouches using dye penetration test with correlation to modeled bacterial aerosol challenge test.* Food Science and Biotechnology, 2017. **26**: p. 947-953.

40. Turner, M., *Product and Package Stability Studies: The Application of FDA Guidance.* Med-Tech Packaging News, 2009(Spring 2009).

41. Millar, S. and M. Desmulliez, *MEMS ultra low leak detection methods: a review.* Sensor Review, 2009. **29**(4): p. 339-344.

42. Schlick-Hasper, E., T. Goedecke, and M. Kraume, *Leakproofness of dangerous goods packagings—comparison of worst-case limit leakage rates and sensitivity of the bubble test.* Packaging Technology and Science, 2019. **32**(6): p. 279-285.

43. ASTM, *ASTM F88/F88M*, in *Standard test method for seal strength of flexible materials*. 2013.