MECHANICAL MODIFICATION OF PACKAGING MATERIAL STRUCTURES

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Tutkimus työssä keskittyi uusien pakkausratkaisuiden kehittämiseen ja innovointiin. Älykkäät pakkausjärjestelmät ovat keskeisenä osana innovaatioprosessia. Tutkimuksen ja kaupallisten pakkausinnovaatioiden pohjalta ideoitiin pakkaustoimintoja. Monista luoduista ideoista kohokuvioidut kehykset älykkäiden pakkausten toiminnoille valittiin jatkokehitettäväksi. Kahdeksan erilaista kohokuviointikehystä ja työkalut niiden valmistettavaksi suunniteltiin. Kehyksillä aikaansaatu suojaus perustui eri toimintaperiaatteisiin. Suojaavat kehykset suunniteltiin kaupallisille NFC- ja RFID-tarroille, sekä tulostetuille johteille. Kehykset valmistettiin kahdelle eri kaupalliselle kartonkimateriaalille, Foodboxille ja Aegle Whitelle. Kulutustestausmenetelmä ja kulutustestauslaite suunniteltiin kehysten testausta varten. Kulutustestauksen tuloksena älykkäiden tarrojen luettavuus ei muuttunut kehysten lisäyksestä. Tulostettujen johteiden resistiivisyys nousi vain hieman kulutustestauksessa, kehyksillä, sekä ilman kehyksiä. Kohokuvioidut kehykset suojasivat johteita ja tarroja kuitenkin naarmuuntumiselta ja muulta kulumiselta. Kulutustestaus laski kehysten profiilin korkeutta. Kehitetyt kohokuviointikehykset toimivat käyttötarkoituksessaan hyvin. Kohokuviointisuojausta voisi käyttää laajemmin tulostettujen toimintojen, kuten viivakoodien tai QR-koodien, suojauksessa.

ABSTRACT

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School of Energy Systems

Mechanical Engineering

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Mechanical modification of packaging material structures

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69 pages, 43 figures, 10 tables and 4 appendices

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This thesis work consists of research and development of new innovations in packaging design, with emphasis on intelligent packaging system integration. Academic research and other innovation sources acted as a basis for innovation process. Based on the research and other packaging innovation sources, number of ideas were created. A selected idea, embossed frames for intelligent packaging features, was developed. Eight different embossing frames were designed, and embossing toolsets were created. Embossed frames have different functional principles in guarding intelligent packaging features. Frames were designed for commercial NFC and RFID labels, and for printed conductor samples. Frames were manufactured on commercial Foodbox and Aegle White boxboard materials. Wear testing procedure and wear testing machine were developed for frames. Results of the wear testing showed no added benefit from frames on readability of RFID and NFC labels, and only slight increase in conductor resistances, with and without frames. Embossed guards provided protection from scratching of labels and especially conductors printed on Aegle White substrate. Wear testing also decreased embossed frame profile height. Developed embossed guards were effective in their designed function. Embossed guards could also be utilized in other printed applications, such as bar codes or QR-codes.

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LIST OF ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
ASTM	American Society for Testing and Materials
bit	Unit of information in computing
CAD	Computer-aided design
CD	Cross machine direction
CTMP	Chemi-Thermo-Mechanical Pulp
DXF	Drawing Interchange Format
Hz	Frequency, Hertz
ISTA	International Safe Transit Association
MD	Machine direction
NFC	Near field communication
Ni	Nickel
P2P	Plate-to-plate
PLA	Polylactic acid
PSA	Pressure-Sensitive adhesive
R2P	Roll-to-plate
R2R	Roll-to-roll
RFID	Radio frequency identification
SEM	Scanning electron microscope
Si	Silicon
Si_3	Trisilirane

Si_3N_4	Silicon nitride
SiC	Silicon carbide
TTI	Time-temperature indicator
UV	Ultraviolet
VFFS	Vertical form, fill and seal

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1 Introduction

The primary purpose of a package is to safeguard and preserve a products’ intended functionality. Secondary purposes of packaging include guaranteeing safety and integrity in transporting and storing the product. However, the functionality of the package is not limited only to primary and secondary purposes. In consumer markets, packaging can act as a market differentiator through various kinds of functionalities and configurations. The role of packaging as a part of the consumer experience is increasingly significant (Steenis et al. 2017, pp. 286-287; Wyrwa & Barska 2017, p. 1681.) Market differentiation can be achieved through innovative new technologies or solutions, that add to the functionality of the package or different kinds of aesthetic enhancements such as embossing and coating methods. In this thesis, new solutions for packaging material modification are studied and developed.

The introduction of intelligent and active packaging in increasingly wider field of industries highlight the new aspect of functionality in packaging. Intelligent packaging enables more accurate product tracking, anti-tamper solutions, and can increase a products lifetime with indicators. (Fuertes et al. 2016, pp. 1-2.)

Intelligent packaging and developments in packaging design have met the demands of consumers for safe and high-quality in food products (Kalpana et al., 2019, p. 145). Intelligent packaging as a part of food packaging is still in the early stages of adoption with estimated annual growing rate of 7% being largest in the United States, Japan and Germany. Even though most common intelligent packaging system in the food industry is time-temperature indicators (TTI), simple electronic detection, indication devices, and radiofrequency-identification (RFID) are implemented in food packaging as well. Intelligent packaging can increase shelf-life, decrease waste, and enhance customer experience. (Fuertes et al. 2016, pp. 1-2; Lee & Rahman 2013, p. 175.)

This work is part of the ECOtronics project, which aims to vitalize Finnish electronics and optics industry, and develop sustainable solutions in the fields of packaging, electronics and optics. This will be achieved by developing sustainable and compostable materials. Minimizing material usage by optimizing materials and components in terms of durability, manufacturability and functionality. The project aims to use life-cycle analysis as a tool to determine the environmental impact of developed solutions. LUT University and Laboratory of Packaging Technology is a part of ECOtronics project and has developed packaging solutions based on the project principles. Resources and materials obtained through co-operation on this project will be used in this thesis work. Research work with intelligent packaging elements, such as RFID and NFC-sensors has been conducted. (ECOtronics 2021.)

The research problem for this study consists of researching and developing new and innovative solutions in packaging design. Intelligent packaging systems are integrated into the development process. Suitable means of manufacturing these new innovations are also studied.

Research questions for this study are:

- What functions can be gained from mechanical modification of packaging materials?
- What are the methods of manufacturing these new modifications?
- What methods are there to test the functionality of these functions?
- How can these functions be utilized in real-world applications?

In this thesis new functions through mechanical modification of packaging materials are developed. Packaging functionality is integrated with intelligent packaging design using packaging sensor technology.

Scale of geometries in mechanical modifications of packaging materials will remain in micrometers at smallest. Smaller, nanometer-scale modifications are still researched, in the hope of gaining insight and possible scalable solutions for this study.

2 Literature review

This thesis starts with a literature study of current trends in packaging, intelligent packaging and the main forms of mechanical modification of packaging materials. Modern applications of fiber-based packaging materials are also researched. Based on findings of the literature study, development of few innovations is pursued.

2.1 Fiber-based packaging materials

Sustainable thinking is an increasingly larger factor determining many manufacturing and design decisions. Because of this, research and development with fiber-based packaging materials is in a large role in the field of packaging technology. The aim is to reduce packaging waste, emissions, and energy consumption. (Kirwan et al. 2013, pp. 205-209.)

When talking about fiber-based packaging materials, paperboard is a broad term that can mean solid or corrugated fiberboard, boxboard, or chipboard (Fellows 2017, p. 987). Paperboard is constructed from pulp, which sources from biobased fibers, such as wood or other plant fibers, making it renewable material. (Riley 2012, pp. 178–179; Robertson 2012, p. 167.) Paperboard has a wide array of material properties that makes it suitable for post processing. These properties depend on the quality of materials and manufacturing, as well as its designed purpose. (Riley 2012, pp. 180–184.) As a packaging material, cutting, creasing, embossing, and gluing are the most common methods in manufacturing paperboard packaging (Coles 2013, p. 188). Fiber-based packaging materials are researched as a replacement for plastic packaging, especially in food packaging (Korhonen et al. 2020, p. 2).

A set of material properties determine the formability of a material. For fiber-based packaging materials, most determining of these material properties are compressive and tensile strength, bending stiffness and elastic modulus. Manufacturing results in machine direction (MD) for fiber-based packaging materials. Cross machine direction (CD) is transverse of machine direction. Microstructural variations within same material account for variation in formability as well. (Johansson et al., 2021, p. 582.) Outside of material properties, manufacturing conditions and used instruments affect packaging material formability (Vishtal et al. 2013, pp. 677–678).

Grammage, a weight of fiber-based packaging material per square meter, reported in g/m2, is also a determining factor of strength properties of a material. When other properties of the material stay the same, a larger grammage determines better strength properties. Material thickness also correlates with grammage, a larger grammage indicates a larger material thickness. It follows that thicker material has better strength properties. Paperboard material thickness is reported in µm. (Kirwan 2008, p. 36.)

Humidity in paperboard manufacturing is another significant variable that affects both formability and material strength properties. Increased moisture decreases paperboard strength properties, which can improve formability. Paperboard material moisture content level adapts to the surrounding environment in terms of humidity. When the humidity is increased for paperboard materials, the material moisture content increases, and vice versa. Differences in paperboard moisture content increase and decrease speed is not constant. Paperboard materials also experience moisture hysteresis, which means that the earlier moisture contents of paperboard affect the moisture equilibrium in which the paperboard settles in new humidity. When moisture is absorbed to paperboard material, fibers in the material swell up. Depending on fiber alignment, changes in physical size will not be symmetrical. Typically, fibers are more aligned to MD than CD. This results in larger physical size difference in the direction of CD. Because of these factors, forming processes of paperboard must take into account the storage environment of paperboard materials on top of environment of manufacturing facilities. (Kirwan 2008, pp. 36–38.)

Temperature is an important variable in the paperboard forming process. When temperature increases paperboard material strength properties and bending stiffness decrease. Temperature increases also decrease the friction between the metallic forming tool and paperboard, which improves the forming process. Humidity and added temperature in forming process act as an interchanging pair of variables. Increased humidity increases friction between the forming tool and paperboard. Increased temperature in the forming process also decreases the moisture content of paperboard. Tearing and bursting can occur at too high moisture contents. (Vishtal et al. 2013, pp. 677–690.)

2.2 Intelligent packaging

Intelligent and active packaging are terms used in reference to packaging systems that increase the functionality of the package beyond its ordinary purpose. These systems are used in, for example, the medical and food industries. Intelligent and active packaging systems can improve logistic chains, inform about the product, monitor product age and freshness, add security and convenience. The terms active packaging and intelligent packaging refer to the same type of packaging systems but cannot be used interchangeably. (Lee & Rahman 2013, p. 172.)

Definition of active packaging by Robertson (2006) defines active packaging as: "*Packaging in which subsidiary constituents have been deliberately included in either the packaging material or the packed headspace to enhance the performance of the package system.*"

Intelligent packaging is defined by Yam et al. (2005): "*A packaging system that is capable of carrying out intelligent functions (such as detecting, sensing, recording, tracing, communicating, and applying scientific logic) to facilitate decision making to extend shelf life, enhance safety, improve quality, provide information, and warn about possible problems.*"

Active packaging functions can be separated into four different types: moisture absorption (adhesives with polymeric fibers), scavengers (oxygen or ethylene), releasing systems (for example, antioxidants) and systems that are embedded in the packaging walls. Active packaging is widely used in the food industry. Intelligent packaging has wider function to sense, share information, or measure attributes of the package. (Lee and Rahman 2013, pp. 172-174.)

According to Lee and Rahman (2013, pp. 174-175), the most common intelligent packaging functions are:

1. Time-temperature indicators (TTIs)
2. Tamper identification
3. Breach and integrity identification
4. Microbial growth inhibition
5. Gas identification
6. Pathogen identification
7. Traceability
8. Anti-theft
9. Radio frequency identification (RFID)
10. Authenticity indication
11. Holographic images and hidden print elements
12. Quality identification

Intelligent packaging elements are separated into three separate categories: indicators, RFID and barcodes, and sensors. Indicators are different types of time – temperature indicators, integrity and gas indicators and freshness and spoilage indicators. Barcodes are a common type of package information system, but with limited in functionality. New types of barcode solutions are in development, such as, Reduced Space Symbology, PDF 417 and Composite Symbology. (Lee and Rahman 2013, pp. 174-176.)

2.2.1 Radio frequency identification

RFID, short for radio frequency identification devices utilizes radio frequency electromagnetic fields to transfer data. In packaging technologies, they are most often found in tag form. Data transfer in RFID systems is used in package product data and product traceability, for example in supply chain tracing. Superior to barcode, RFID can be read from a distance of up to 100 meters and without the need of RFID tag being in line of sight of reader. RFID also allows reading multiple products simultaneously, up to 100 units per second, and in future even 1000 units per second. A typical RFIF tag used in packaging is shown in Figure 1. In addition to tag, RFID system consists of reader or interrogator and central node, typically a computer, shown in Figure 2. (Lee and Rahman 2013, pp. 188-191.)

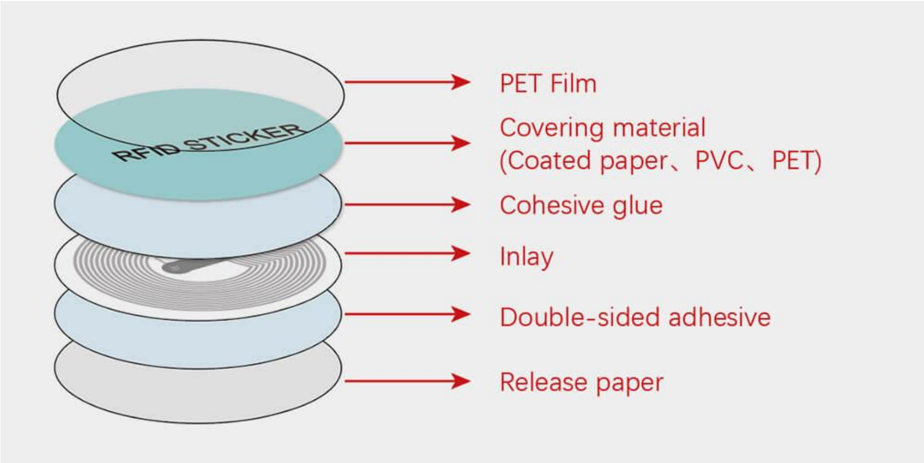


Figure 1. A typical structure of a traditional RFID tag (RFID MC, 2021).

There are three types of RFID systems: active, passive and semi-active. Passive RFID tag has no power supply and works from the signal sent by the reader. Active RFID tag has battery which increases the functionality of the tag. These functions are longer readability range, more communication functions in the form of sending in addition to only read function, monitoring or included sensors. (Lee and Rahman 2013, pp. 189-192.)

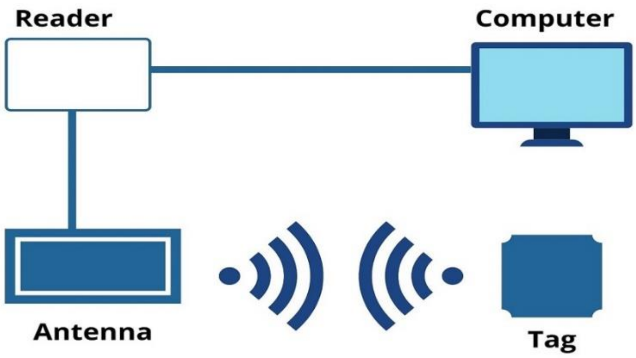


Figure 2. RFID system components (Libcon 2020).

Semiactive RFID system has increased readability compared to passive RFID system. This is made possible by small battery in semiactive RFID tag. (Lee and Rahman 2013, p. 191.)

2.2.2 Near field communication

Near field communication (NFC) uses RFID technology for shorter range data transfer. The transfer distance between the reader and NFC device is only a few centimeters. NFC uses operation frequency of 13.56 MHz, with transfer rates of 106, 212, and 424 Kbits per second. Most common applications for NFC are mobile phone pairing, contactless payment option in debit cards, and mobile phone contactless payment. (Coskun et al. 2015, pp. 2-7.)

2.3 Mechanical modification methods

In this section mechanical modification methods for packaging materials, most importantly fiber-based packaging materials are listed. The most suitable modification methods are utilized for the experimental part of this work.

2.3.1 Embossing

Embossing is a good way to perform micro and nano scale mechanical modifications to a wide range of materials. In embossing, the material is pressed against molds to the desired form with mechanical force. Increased temperatures or ultraviolet (UV) light can be used to assist this process. Increased temperature increases the formability of embossed material. With UV light, an additional material is added and then hardened using UV light. The most common ways to perform embossing is with flat plates or rollers or combining both. Small and sharp shapes are possible to manufacture when embossing polymer. Hot embossing, UV imprint and soft imprint are three main embossing methods. Materials containing polymer are embossed using hot embossing or UV embossing, depending on the method of hardening. Common embossing die materials are Ni, Si, Si_3N_4 or SiC. (Izdebska, Thomas 2016, p. 279.)

In packaging technology embossing us usually used for appearance improvement. It has, however, ways to increase functionality, identifiability, and safety of the package (Tanninen et al. 2019, pp. 1-2). Another use of embossing in packaging technology is in batch coding, where each batch of products is coded for batch differentiation and tracking. This method is usually called letter press printing, where ink can be applied simultaneously. (Crompton 2012, p. 521.)

2.3.2 Hot embossing

Hot embossing process has been used in wide variety of industries for over 40 years. First used in replicating holograms on vinyl tape, to currently capable of doing nano-scale imprinting, making hot embossing a nanoimprinting technology. (Izdebska, Thomas 2016, p. 280.) Hot embossing, visually demonstrated in Figure 3, process can be divided into four steps:

1. Heating up the mold and possibly embossed material to molding temperature
2. Molding process by isothermal forces and mechanical forces

3. Cooling the mold and material to demolding temperature, maintaining constant mechanical molding force
4. Demolding, removing molding forces

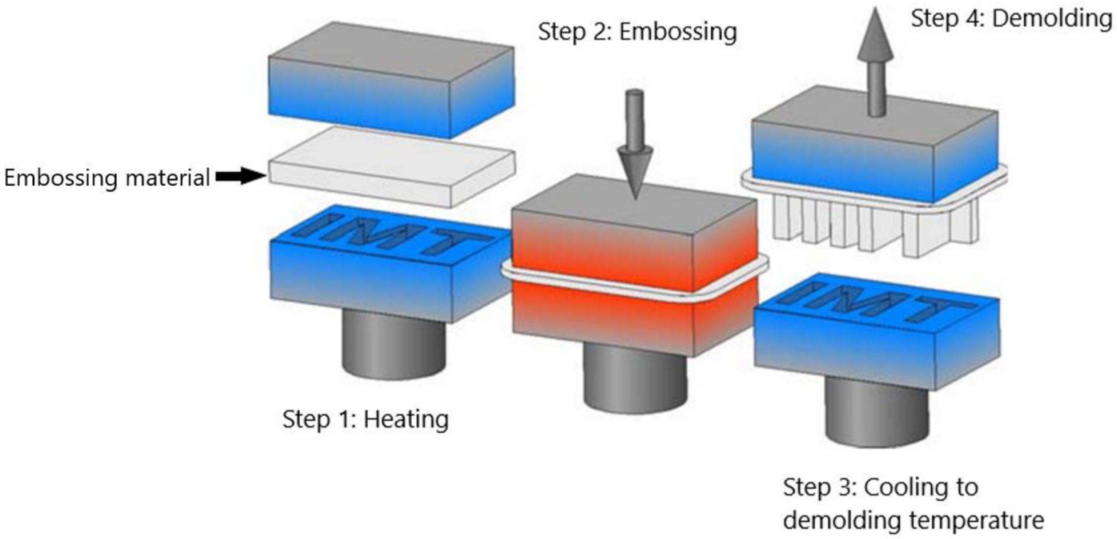


Figure 3. Hot embossing process steps (Modified from Worgull et al. 2008, p. 1062).

The hot embossing process is separated into three different types based on forming tools and their configuration. Forming tools are either plate or roll, shortened to P and R. Plate-to-plate, roll-to-plate and roll-to-roll embossing mode principles are shown in Figure 4. (Izdebska, Thomas 2016, p. 280.)

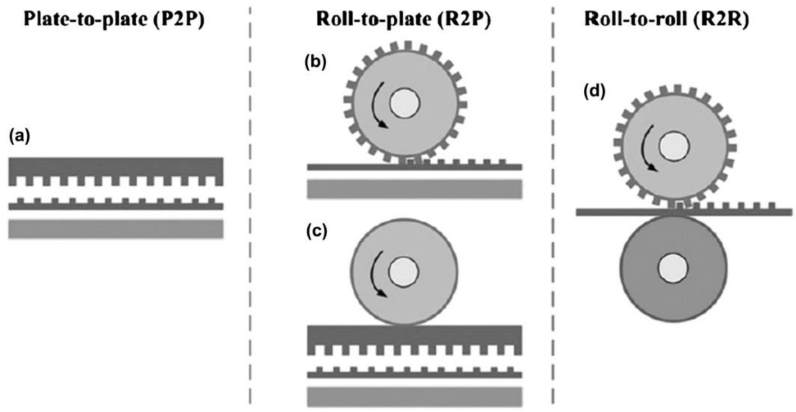


Figure 4. a) P2P, b) R2P-roller mold, c) R2P-flat mold d) R2R embossing mode principles (Izdebska, Thomas 2016, p. 281).

2.3.3 Plate-to-plate embossing

Plate-to-plate (P2P) embossing, shown in Figure 4 a, is a traditional embossing process consisting of two flat plate forming tools. The main variables when using P2P embossing are forming tool temperature, force and forming time. Other notable variables in this process are tool quality and demolding time. P2P embossing is done in batches, and continuous manufacturing is not possible. Additionally, compared to other embossing methods, P2P embossing has large forming forces and usually a smaller continuous forming area. This makes the process less efficient than other embossing methods. It is used widely in multiple industries, such as forming CD and DVD discs. (Izdebska, Thomas 2016, p. 280.)

2.3.4 Roll-to-plate embossing

Roll-to-plate (R2P) embossing, shown in Figure 4 on parts b) and c), consists of a roller as upper forming tool, and a flat plate as the lower forming tool. Roll-to-plate embossing has the advantage to P2P with increased forming surface. R2P embossing system has heating and imprinting on the roller. Demolding in this system is continuous, and not simultaneous as in P2P embossing. (Worgull 2009, p. 163; Izdebska, Thomas 2016, pp. 281–282.)

2.3.5 Roll-to-roll embossing

Roll-to-roll (R2R) embossing, shown in Figure 4 on part d), consists of two forming rolls, enabling continuous forming with continuous demolding like R2P embossing. Typically, one of the rolls contains both heating and imprint, and the other roll has a smooth surface. R2R embossing is very effective method of creating continuous imprint on materials. The main variables in R2R embossing are feed speed, forming temperature and forming pressure. (Worgull 2009, p. 163; Izdebska, Thomas 2016, p. 282.)

2.3.6 Press forming

Press forming and folding are two of the most common ways to manufacture trays out of paperboard material. Paperboard used in press forming is typically polymer coated. The main components press forming are a male mould, female mould and rim tool. This is illustrated in Figure 5. The female mould is heated up to moulding temperature T1. Typically, paperboard, with no polymer coating, is held against the female mould that is higher in temperature, to enable formability, without the possibility of burning the polymer coating.

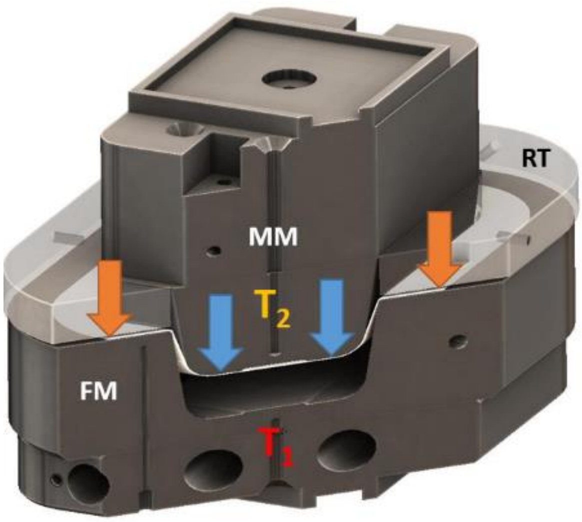


Figure 5. Press forming mould setup, male mould, female mould, rim tool, and forming forces (Tanninen 2015, p. 19).

During the press forming process, a male mould presses a precut cardboard blank against a female mould with forming force. The rim tool controls the slipping of the blank, enabling the correct amount of plastic deformation, and folds flanges to formed tray. The male mould is pressed for a duration of a dwell time, which lets the polymer of the paperboard to set and fuse creasing of the tray. For the last step of the process, male mould is lifted, and the tray is removed set to cool for finished result. The main variables in press forming process are pressing force, blank holding force, heating temperature and pressing speed. (Tanninen 2015, pp. 19-20.)

2.3.7 Creasing

Creasing a material means pressing recessed lines to enable the next step of folding or other modifying process for the material. For paperboard, creasing enables folding and press forming, without material cracking. Paperboard folding usually includes gluing or other joining methods to make a finished product. Creasing is done using creasing rules, which are thin metallic strips. Rules are rounded at the ends, so that they enable the pressing lines into the material without cutting it. Figure 6 illustrates working principle of creasing. Paperboard is under compression and elongation forces during the process. (Tanninen, 2015, p. 18, 25.)

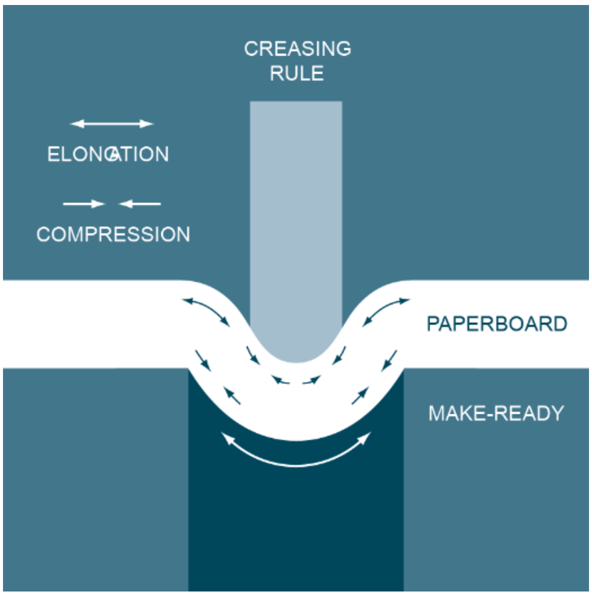


Figure 6. Creasing working principle (Iggesund 2021).

In press forming, creasing has an entirely different function than in folding. In press forming, creases enable forming of round corners for the tray, controlling locations where the folding happens during the process. The difference between creases in folding and tray forming are shown in Figure 7. (Tanninen, 2015, p. 18, 25.)

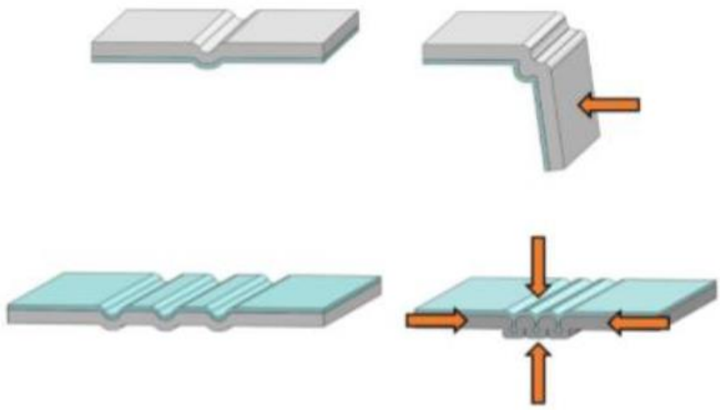


Figure 7. Difference of effects of creasing in folding (upper image) and press forming (lower image) (Tanninen 2015, p. 18).

2.4 Package testing

Package testing consists of large amounts of different types of tests, for different types of package materials and products. Everything from transport to environmental effects is tested using standardized methodology. Tests are aimed specifically to make sure the intended functionalities of the package work under the intended circumstances. Package testing must clearly state the purpose of a specific test, how the test is concluded and how the results are gathered and analyzed. The aim of package testing is to gather information about the package's performance. Well-designed testing for packages guarantees results that can be applied in research and development of the product. Two of the most common packaging standards used in packaging testing are ASTM International standards for package testing and International Safe Transit Association (ISTA) standards. Examples of package testing include conditioning and atmospheric testing, vibration, strength, compression, friction and shock and impact testing. (ASTM 2021; ISTA 2021.)

For abrasion resistance testing of printed packaging materials rub tester method recommended. When using a rub tester, a flat test sample is attached to the receptor block, which moves in an arc along a surface. The receptor block has added weight for increased abrasion. Sutherland rub tester with attachments is presented in Figure 8. (ASTM D5264 2019.)

Figure 8. Sutherland 2000 rub tester and attachments. (Rubtester.com 2021)

3 Materials and Methods

As the aim of this work is to research and develop new possible solutions in modifying packaging materials, section of this work focuses on an idea generation process and the available resources and tools. During the development process multiple ideas are gathered and generated, from which the most viable ones will be pursued further into actualized prototypes.

3.1 Materials

Main paperboard materials used in this work are Foodbox and Aegle White. These materials are used in ECOtronics project and are chosen for this work for this reason. These are commercial materials manufactured by Stora Enso and Kotkamills, respectively. Foodbox is 3-layered uncoated boxboard material. Three of its layers are fiber construction, top two layers being made of bleached sulphate pulp. Middle layer of the material is chemi-thermo-mechanical pulp (CTMP). In Table 1 grammages and correlating boxboard thicknesses for Foodbox are presented. Foodbox is a renewable and sustainable packaging material that can be used in food product packaging. When talking about specific paperboard material, grammage is often reported after the material name. (Stora Enso 2021; Kotkamills 2021.)

Table 1: Grammages and thicknesses of Foodbox boxboard (Stora Enso 2021).

Grammage (g/m^2)	230	233	257	273	297
Thickness (µm)	370	402	450	465	505

Aegle White is a foldable boxboard manufactured by Kotkamills. It has a 5-layer construction. Aegle White consists multiple coatings of topcoat, two bleached chemical pulp layers, CTMP, and single bottom layer coating. Aegle White is a sustainable and renewable boxboard material, applications designed for confectionary pharmaceutical, cosmetic, other premium packaging, and other graphical end uses due to its good printability. In Table 2 grammages and correlating boxboard thicknesses for Aegle White are presented.

Table 2: Grammages and thicknesses of Aegle White boxboard (Kotkamills 2021).

Grammage (g/m^2)	200	210	220	235	245	255	270	280	290	305	330	355
Thickness (µm)	285	305	325	355	375	395	425	445	470	500	550	600

Kinetic friction coefficients have also been measured for Aegle White 290 and Foodbox 230 boxboard materials. They are presented in Table 3. MD and CD for boxboard materials have separately been measured. (Pesonen, 2021)

Table 3: Coefficients of kinetic friction for Aegle White 290 and Foodbox 230 boxboard materials.

	Coefficient of kinetic friction	
Material	MD	CD
Aegle White 290	0,31	0,31
Foodbox 230	0,44	0,43

ECOtronics project materials

LUT packaging laboratory has developed embossing methods with intelligent packaging labels as a part of ECOtronics project. Figure 9 shows embossing toolset used to manufacture protective frames around commercial RFID and NFC labels.

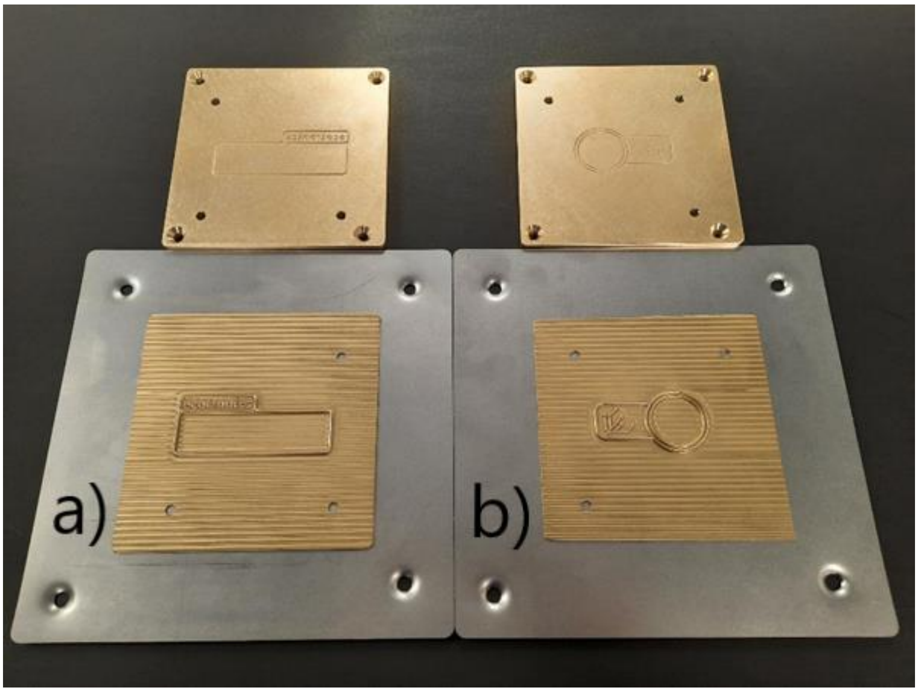


Figure 9. Embossing tools for protective frames for commercial a) RFID and b) NFC labels that include ECOtronics project logos.

Used labels are manufactured by Stora Enso. The RFID label is Stora Enso's ECO Rack RAIN RFID label, that is intended for singular retail product tracking. Comparable to traditional intelligent packaging labels, it consists of face paper, antenna, pressure-sensitive adhesive (PSA) and release liner. Figure 10 shows comparison to the traditional RFID structure.

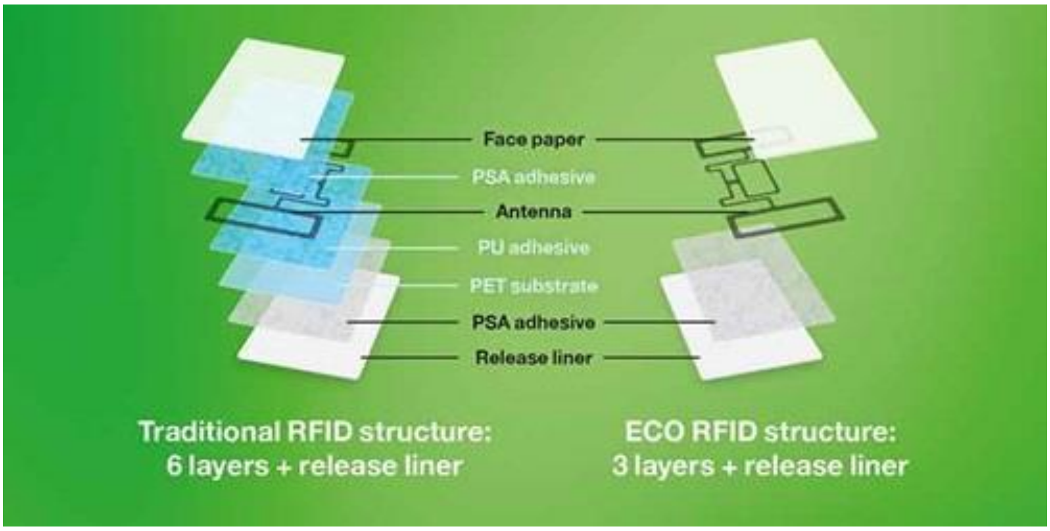


Figure 10. Comparison of traditional and ECO RFID structures (Stora Enso 2021).

The size of the label is 72 x 17 mm, which is suitable for commercial item level tracking. The label working frequency is 860-960 MHz. Its theoretical read range is from 4 meters up to 17 meters, based on the frequency used and the medium that is between the reader and label (cardboard, plastic or air). Operating temperature for the tag is from -5 °C to 60 °C. Because of its fiber-based materials, lack of plastics and waterless antenna manufacturing, it is marketed as sustainable solution in RFID tracking. For near field communication, Stora Enso's Bobbin NFC label is a 22 mm round diameter tag. It has read range of up to 40 mm and operating temperature from -5 °C to 60 °C. It is designed for retail packaging tracking and information sharing with password protection for product authentication.

Another resource for this thesis and ECOtronics project is inkjet printed conductor samples, manufactured in Tampere University (TAU). These conductor samples are printed on two different substrates, Aegle White 290 and Foodbox 230 boxboards. The size of the substrates for printing were 210 x 297 mm, which is international paper size A4. The inkjet printing process uses ANP-15C ink in 4 layers. Drop spacing for the process is 30 µm and samples were sintered in 130 °C for an hour. Figure 11 demonstrates a) geometry and size of the printed sample and average result on b) Foodbox and c) Aegle White substrates. As Figure 11 shows, Foodbox as a substrate experienced higher wetting, where the ink spreads along fibers of the substrate. Average TAU measured resistances of conductors printed on Aegle

White was 12,2 Ω and for Foodbox 2,7 k Ω. Foodbox experienced larger deviation on resistances. (TAU, 2021)

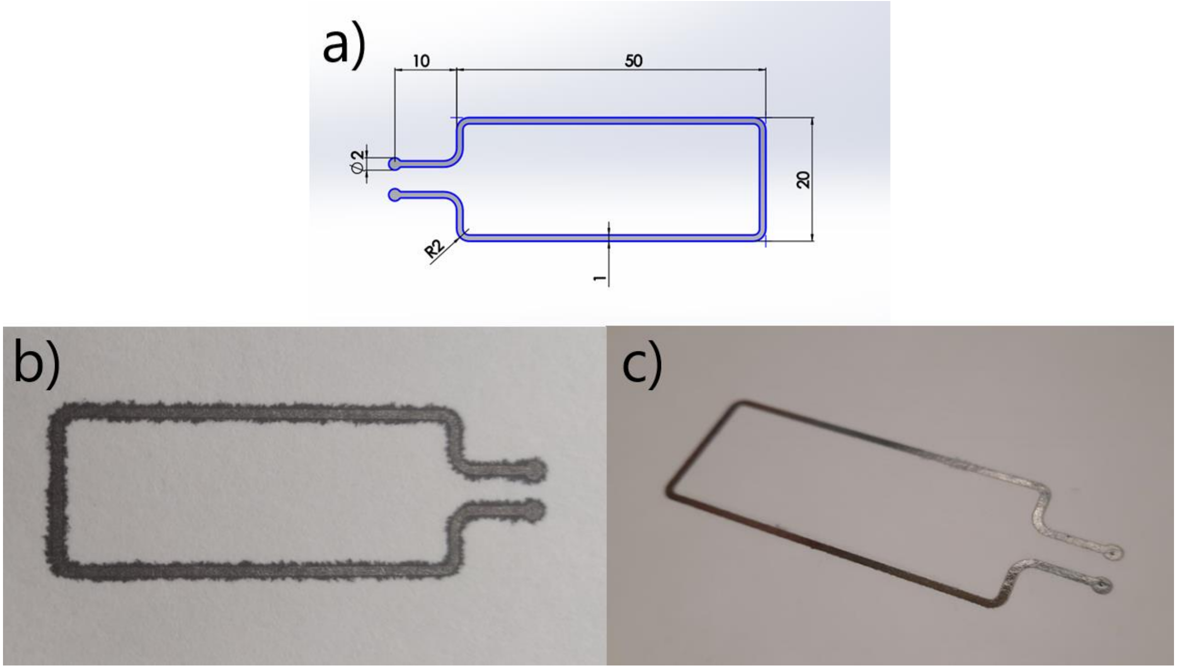


Figure 11. Printed inkjet samples. a) Geometry and size (in mm) of printed samples b) on Foodbox c) on Aegle White.

For this project, 30 samples of printed conductors on Aegle White 290 substrate and 8 samples on Foodbox 230 are provided.

3.2 Methods

Modelling tools

A large part of this work includes designing and modelling new concepts and solutions. Visual illustrations for prototyping and ideating are used. Computer-aided design, in short CAD, is the use of computer programs and systems in designing two-dimensional (2D) and three-dimensional (3D) illustrations and models. Modern design and manufacturing use CAD in many ways, from design and illustrations to manufacturing plans. During ideation phase CAD is used to outline design directions and ideas more roughly. Models are used to illustrate the basic idea and functionality of the design, rather than fully design manufacturable product or tool. With paperboard manufacturing sometimes 3D-modelling of the designed paperboard product will only be used in demonstration, and actual 3D-models that are used in manufacturing are the tools creating the paperboard product.

Main CAD utilizing program in this work is SolidWorks, published by Dassault Systèmes. Design progress with SolidWorks starts with modelling 3D parts and assemblies. 3D models can be converted to 2D manufacturing and design drawings. SolidWorks models can also be converted to many types of file types for manufacturing, for example AutoCAD Drawing Interchange Format (DXF) file format, which is used in large variety of manufacturing programs. SolidWorks has wide array of simulation tools, as add-ons, from topology optimization to acceleration and collision detection. On top of these reasons, ECOtronics project design models and assemblies in LUT are designed using SolidWorks, so unified and compatible model catalogue is a large plus. For example, embossing tooling was designed using SolidWorks, shown in Figure 12.

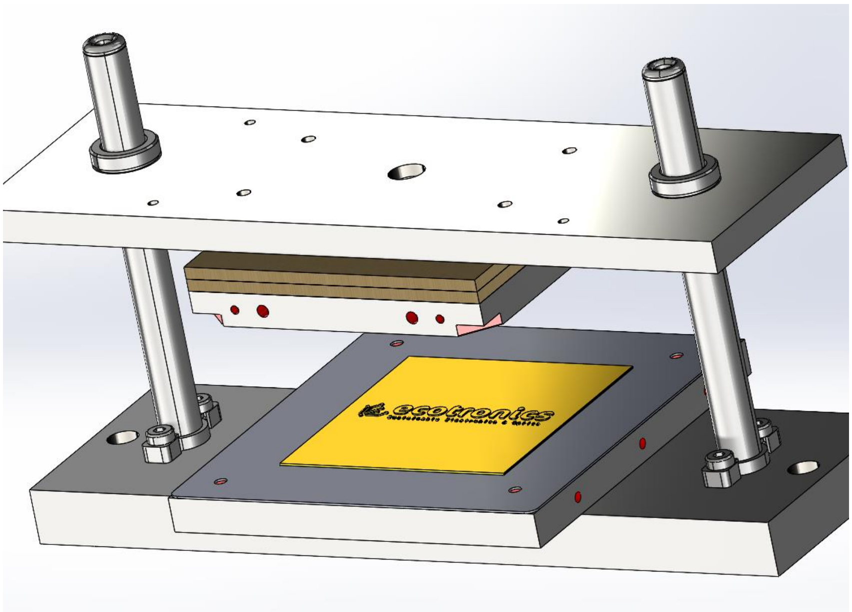


Figure 12. Embossing tooling and tool holding configuration in SolidWorks.

Inkscape is a program developed for producing vector images. It is an open-source software. As SolidWorks is not capable of producing vector images, Inkscape is used in this work for all 2D vector imaging. Vector graphics have advantage in scalability, and some manufacturing programs use vector graphics.

3.2.1 Ideation process

As was mentioned in the introduction, packaging technology can be said to be a mature technology. A large amount of research and development has been conducted in the field of packaging technology since its introduction. This doesn't however stunt the growth of innovation, as newer packaging technology areas, such as intelligent packaging, have emerged. Because of these two factors, the ideation process for this topic starts from understanding and learning about established methods and methodology of manufacturing, design and function of packaging as a field. On top of that, learning about newer branches of packaging innovation is as important. The literature review section of this thesis and research process for it acts as a basis for ideation in mechanical modification of packaging material structures. The literature review process includes research on peer-reviewed journals and other academic sources in the field of packaging and packaging materials. A closer look in emerging packaging technologies and studies that list and review the state of the art of each subsection of packaging technology. This academic side for the basis of innovation gives grounded and thorough understanding from which to innovate. Other side of basis for innovation process is resources from commercial packaging manufacturer's products and commercial information sources. In these are included packaging news websites, packaging information websites, manufacturers' own released information on new innovations, and other forms of packaging media, packaging design and innovation videos found on the internet.

Using academic and commercial resources as a basis for innovation, the main innovation process used in this study is brainstorming, mostly done individually but also in a group. Figure 13 illustrates the general innovation process in this work. Figure 13 intentionally highlights the larger importance of academic resources compared to commercial resources.

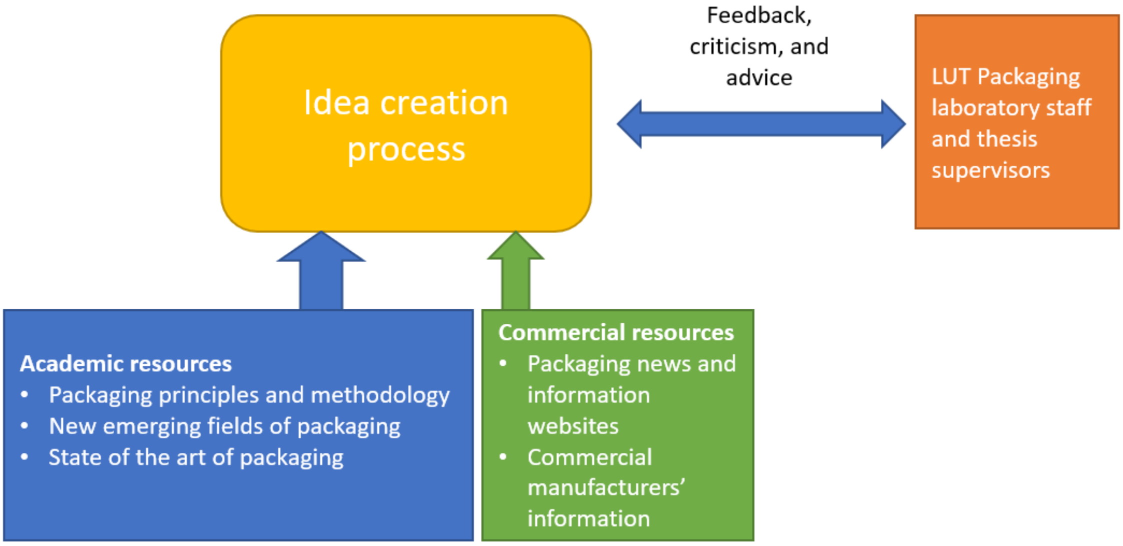


Figure 13. Idea creation process.

In brainstorming, the idea is to identify a problem or a feature that is wanted to be achieved and then generating large number of solutions. From these solutions follows a process of scrutiny and feedback, and the best solutions are refined, as more cycles of scrutiny and feedback is exercised. In this mostly feedback, but also some brainstorming process is concluded with LUT packaging laboratory staff and supervisors of this thesis. Their assistance with knowledge and experience in the field of packaging helps guide the innovation process. As is with most thesis works, scheduled meetings are held. For this work, during the innovation stage these act as innovation and feedback sessions as well. From generated pool of ideas, chosen few are developed further.

3.2.2 Testing methodology

In this section is listed testing methodology for developed in this thesis and utilized LUT laboratory packaging equipment and machinery.

Experimental testing procedure has two variations, one for embossed intelligent label guards, and the other for printed conductor sample guards. Testing procedure for intelligent label embosses is shown in Figure 14.

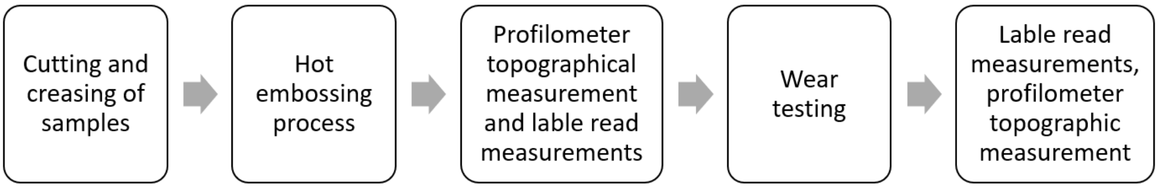


Figure 14. Testing procedure for embossed guards for RFID and NFC labels.

Printed conductor sample testing procedure is shown in Figure 15. Instead of intelligent label readings, resistance is measured before embossing, after embossing and after wear testing. Resistance measurements are conducted on multimeter with accuracy of ± 0.1 Ω. The effect of embossing and wear testing on conductor samples is studied.

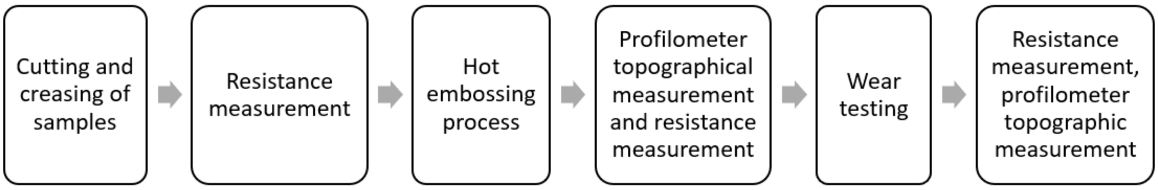


Figure 15. Testing procedure for embossed guards for printed samples.

Testing samples

Testing samples were separated in two different groups, printed conductor samples and RFID and NFC label samples. Due to the restrictions of size of A4 printed conductor samples, the two different group of samples were cut with different sized flanges that attach to the sample holding box. Both sample sizes are illustrated in Figure 16. Grey lines illustrate creasing lines on samples, that are folded to the sides of sample holder.

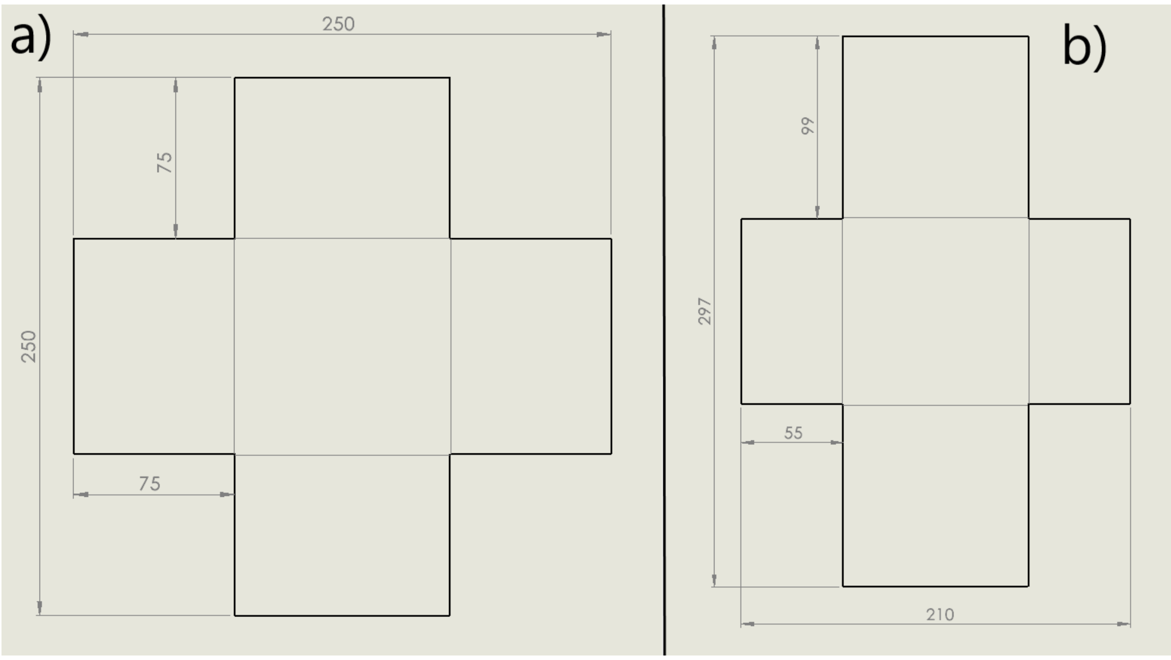


Figure 16. Sample sizes in mm of a) RFID and NFC label emboss samples b) printed conductor samples.

Samples are cut and creased using Kongsberg XE10 sample maker. Kongsberg XE10 dieless digital cutting and creasing table is intended for paperboard. Kongsberg XE is shown in Figure 17. Its work area is 800 x 1100 mm with maximum sheet size of 1000 x 1500 mm.

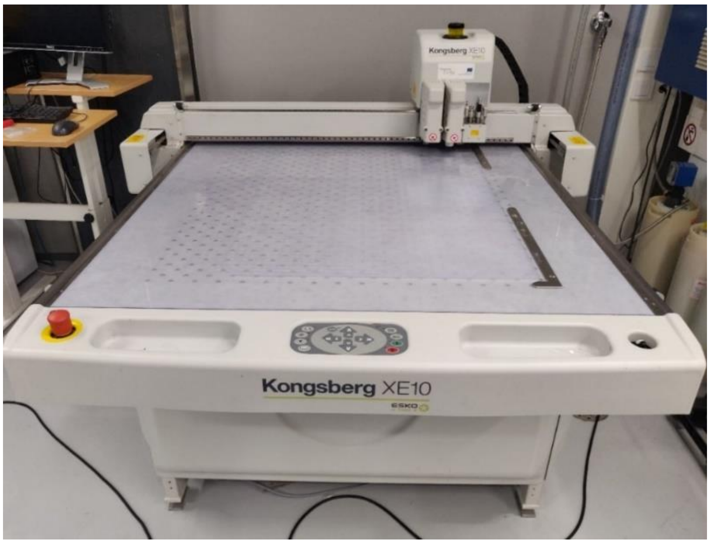


Figure 17. Kongsberg XE10 digital cutting and creasing table.

Maximum speed of the machine is 64 m/min. Reported repeatability accuracy is ± 20 µm. Kongsberg XE10 is capable of both creasing and cutting paperboard on same run. It has different tool stations with creasing and cutting tools for different types of paperboard structures. Kongsberg XE10 uses ACM ArtiosCAD file format for cutting and creasing patters. Test samples are cut and creased from Aegle White 290 and Foodbox 230 boxboard material with sample cutter. Samples are held in normal laboratory atmospheric conditions before embossing.

Embossing

Main area of manufacturing in this thesis is embossing. Embossing setup contains Shimadzu AGS-10kNX universal testing machine, shown in Figure 18, and controlled heating unit and heating elements, shown in Figure 19. Shimadzu machine is equipped with embossing rig, on which to attach embossing tools. Embossing rig also includes heating elements. This is illustrated in Figure 19. Shimadzu AGS-10kNX test force accuracy is within ± 1% of indicated result. For printed sample embossing positioning tools were also developed and utilized.

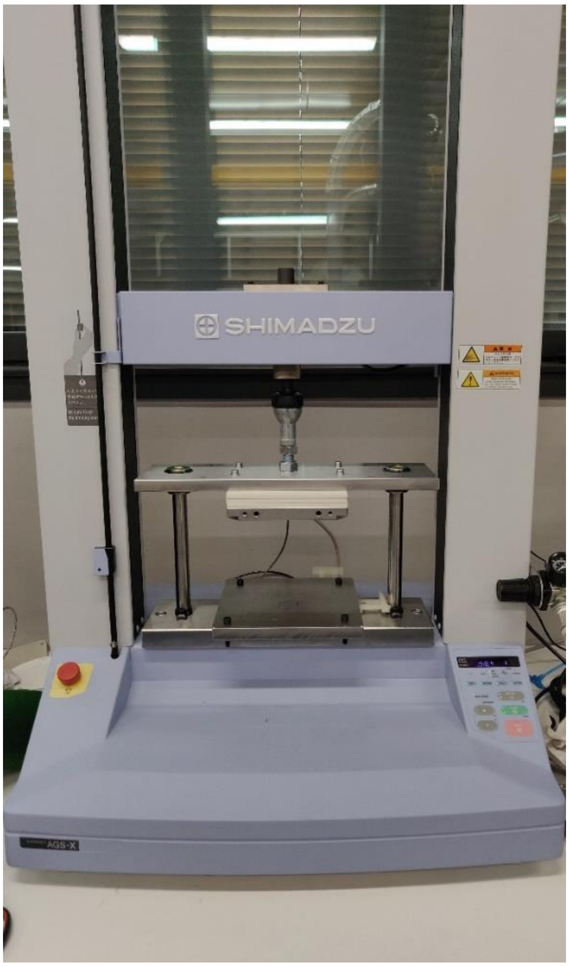


Figure 18. Shimadzu AGS-10kNX universal tester with embossing rig.

Figure 19. a) Heating elements on upper tool and b) Tempatron heating controller.

All embossing tools designed during this work are used and ECOtronics project embossing tools with logos, toolsets 3 and 4, shown earlier in Figure 9, are also used for comparison. Embossing procedure parameters were set for all samples at 6 kN embossing force and 80 °C heating temperature on embossing tool. The positioning of the embossing tool is linear until 6 kN force is reached, and the tool is lifted after 1 second hold time. The embossing parameters were already optimized previously as a part of ECOtronics project.

Alignment of printed samples on A4 sample substrates was not identical with one another, so additional step for completing hot embossing positioning for printed samples was performed. Each printed sample conductor outlines were copied on positioning samples, and with developed positioning tools and positioning embossing runs, embossing of printed samples was completed. Positioning tool model is shown in Figure 20. Positioning tools are attached at the end and right side of lower embossing tool.

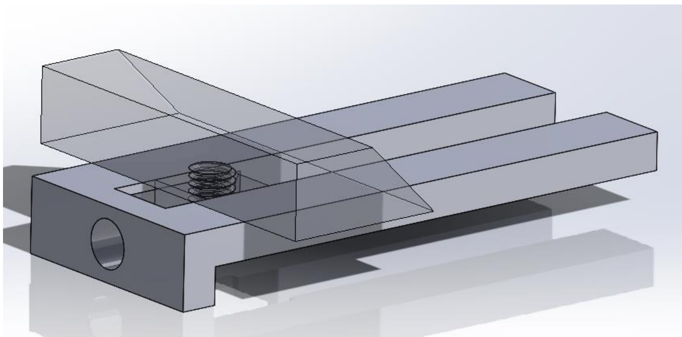


Figure 20. Positioning tool model. Upper part of the tool is transparent to illustrate threading.

Positioning tools were modelled and 3D-printed from polylactic acid (PLA). Positioning tools have holes for attachment to embossing lower tool and M6 threading for fastening accurate positioning.

Wear testing

Wear testing machine is developed in this work. Development and more detailed construction of the machine is presented in results section of this thesis. Figure 21 illustrates developed wear testing machine.

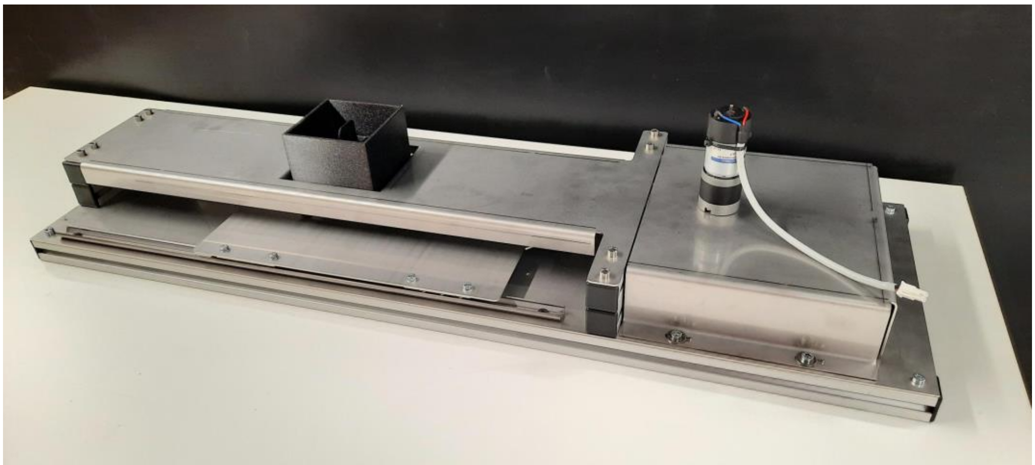


Figure 21. Wear testing machine for embossed samples.

Wear testing samples are attached, one sample at a time, to the sample holder with rubber band on the flanges. Wear testing is carried out at one complete 200 mm motion of wear plate per second (0.5 rpm on electric motor). Added weight of 240 g on the sample box is added to simulate contents of the package. The wear testing is done for 10 minutes per sample, with sample turn at the 5-minute mark for two-directional wear effect. Wear material at the wear plate is same as sample material, A4 size boxboard flat samples are attached to the wear plate.

Profilometer

Keyence VR 3200, shown in Figure 22, is a non-contact optical 3D profilometer. It is used to measure topography of an objects surface. Height measurement accuracy for Keyence VR 3200 is reported ± 3 µm, and height measurement accuracy ± 5 µm. The profilometer creates a 3D digital profile of the selected scanned area. After sample embossing is completed, topographical measurements with profilometer are taken.

Figure 22. Keyence VR 3200 profilometer.

Reader

Nordic ID HH83, pictured in Figure 23, is a wireless handheld reader for barcodes, UHF RFID, and NFC. It includes item information logging and inventorying software. Reference reading on both NFC and RFID labels is taken with Nordic ID reader.

Figure 23. Nordic ID HH83 handheld reader.

Samples are measured RFID label facing up and perpendicular to the reader. Samples are at the same height as the reader, 1,3 meters from the ground. With NFC labels, readability of the label is either positive or negative. RFID labels' read distances are measured in meters.

SEM

A scanning electron microscope, SEM for short, utilizes a beam of electrons in image creation. It scans the surface of an object with the beam of electrons to create an image from topographical and composition data. LUT laboratory has Hitachi SU3500 SEM machine with tungsten filament equipped. SEM machine is shown in Figure 24. SEM machine has two modes, secondary electron imaging (SEI or SE) and backscatter electron imaging in compositional mode (BSE-comp). In SEI the accelerating voltage is 10 kV and in BSE-comp 20 kV. SE was mostly used in this work. All the samples were sputter-coated with Au/Pd before imaging.

Figure 24. Hitachi SU3500 SEM machine and controlling station.

Different embossing conditions will be conducted on the most effective label guard, based on first round of testing. Embossing for these samples will be conducted two different ways. First, embossing without heating, at room temperature, approximately at 23 °C. The second way is embossing samples that have been stored at 80% relative humidity (RH) in humidity conditioning cabinet. Embossing without heated tools will also be conducted on embossed conductor frames. These tests are to study if embossing without heat has any significant reduction in effectivity of the emboss, and if increasing moisture level of the embossed sample increases effectivity noticeably. Additionally, wear testing on conductor frames and most effective label guard is conducted with against steel wear plate with no added material. Chosen conductor samples and label guards will be analyzed more closely with SEM.

4 Results and discussion

In this section of the results of the ideation process are presented. The ideated paperboard functions and features lead to further refinement and creation of tools and methods for manufacturing them. For created paperboard features testing methodology was produced listing specific required equipment and methods. At the end of this process created features and results from testing methods are analyzed numerically and visually.

4.1 Ideation results

Boundaries set for ideation process were the use of packaging materials, and ways of obtaining functionality through mechanical modification of those materials. Some of the ideas generated through this process are then able to be manufactured, at least on the time scale of this work. Literature research, for this reason, focused more on manufacturing methods that were already in LUT packaging laboratory, such as sample making, tray press forming, and embossing. Research on state-of-the-art innovation in packaging focused mostly on intelligent packaging and food packaging and an overlapping of innovations were found in TTIs and other sensing packaging features. LUT packaging laboratory’s manufactured press form trays and vertical form, fill and seal (VFFS) bags, illustrated in Figure 25, were also a template from which to innovate and try to improve.

Figure 25. Printed press formed trays and VFFS bags manufactured at LUT. Modified from (LUT 2021; Merabtene 2020)

Generated ideas are presented in tables 4-6. Ideas are separated in packaging surface modifications, Table 4, packaging features, Table *5*, and whole packaging solutions, shown in Table 6. The tables present a brief idea description, idea number and figure illustrating the idea. Some ideas presented in the tables were developed further than others. The ideas presented in the tables are in no particular order, and not all ideas have illustrating figures. All ideas generated through this process focused on fiber-based packaging materials, due to its popularity in packaging and manufacturing capability. The most common manufacturing method for these ideas turned out to be embossing, and various embossing methods.

Table 4: Ideated packaging surface modifications.

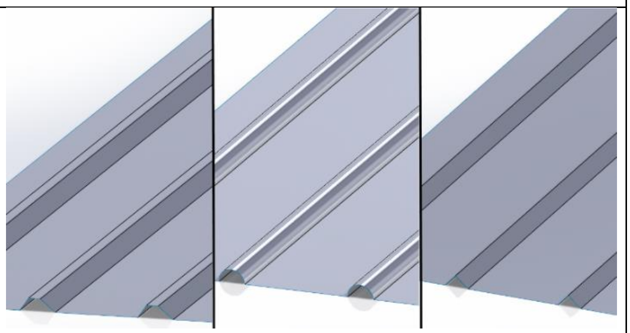
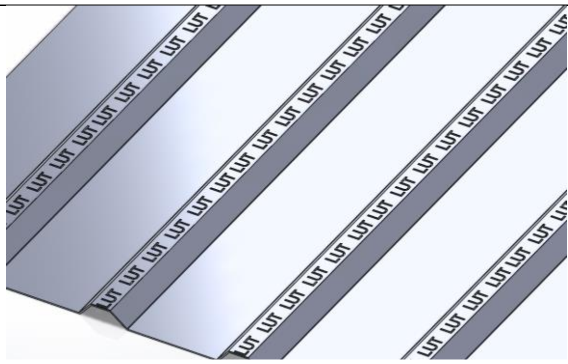
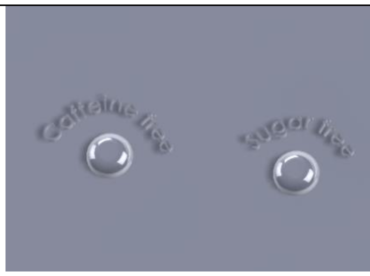
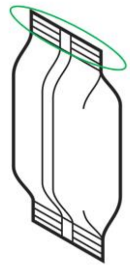
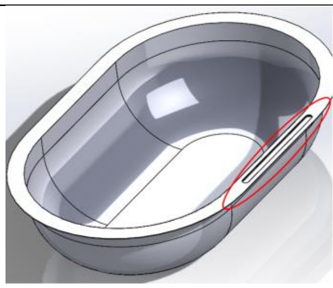
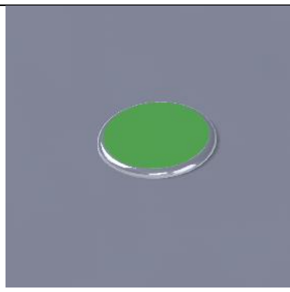
Idea number	Description	Figure
1	Increased friction through modified macro-size shape modification. Triangular, circular or hexagonal shapes to increase surface roughness and increase friction. Mostly for paperboard materials manufactured with embossing method.	No figure available.
2	Increased bending resistance and friction through paperboard material modification. Possible manufacturing methods are embossing or integrated in paperboard manufacturing rollers.	
3	Branded material embossing. LUT branding throughout paperboard material. Includes material modification for bending resistance and friction. Manufacturing possibilities through embossing or integrated roller system in paperboard manufacturing.	

Table 5: Ideated packaging features.

Idea number	Description	Figure

4	Pressing function for paperboard packaging. Information about contents of the package are presented in the package through embossing or printing. Pressing embossed raised button to inform about contents.	
5	Intelligent packaging sensor or component integration to vertical form fill seal machine. Intelligent component inserting inside seal of the bag. Component inserting apparatus would be integrated to heat sealing clamps. Possible components could include RFID or NFC tags. In figure green circle is the position of the sensor and red circle indicates the application place in sealing jaws.	
6	Intelligent packaging component insert to press formed trays. Embossing feature would be done in flange of the tray. Embossed insert feature could provide product tracking or information.	
7	Increased stackability of packages. Stackability increasing interlocking features on top and bottom of packaging material. Possible manufacturing method would be embossing.	No figure available.
8	Embossed Quick Response code (QR-code). Embossed matrix code structure on packaging surface. This would improve product authentication and reduce copyability. Embossed QR-code could be improved with different ink coloring options.	No figure available
9	Improved visibility for TTI with embossing/debossing. Embossed surface to increase the visibility of TTI on packaging.	

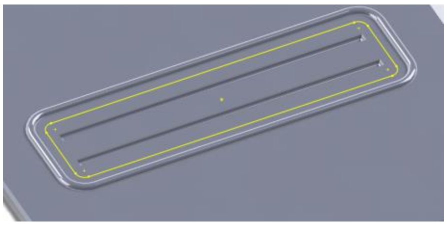
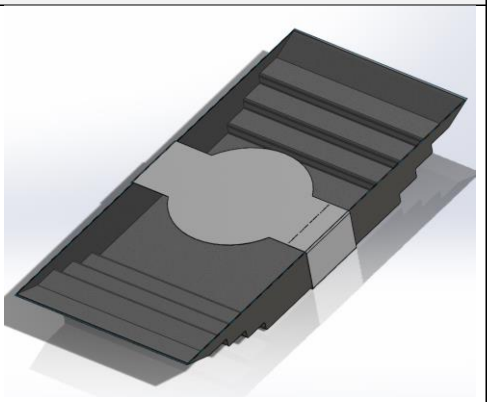
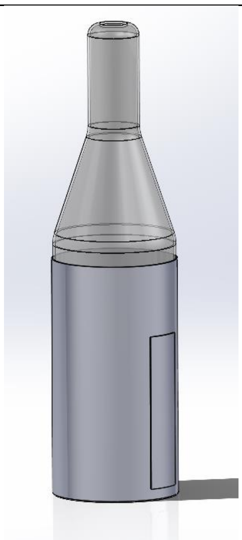
10	Embossed guards for intelligent packaging labels and tags. Guards would have improved properties, for example stiffeners or wider embossed edges. Material would be paperboard and manufacturing hot embossing.	

Table 6: Ideated packaging solutions

Idea number	Description	Figure
11	Paperboard banderole around plastic packaging. This banderole would include folded or embossed slots for intelligent packaging components. Manufacturing methods could be in prototyping with sample maker.	
12	Multipurpose bottle etiquette that can be used as a drinking cup. Bottle etiquette that is removable from the bottle. The mug would also have folded paperboard handle construction. Two different configurations are possible. One with single cup and other with two cups facing each other and acting as a bottle package. Remaining part of the etiquette would contain important content information and remain on the bottle.	
13	Folded paperboard lid construction for paperboard cups.	No figure available.

Due to the available materials and methods, the quality of ideas, and consensus, idea number 10, embossed guards for intelligent packaging labels, in Table 5, was chosen to be developed further. Embossing guard feature were to be developed into several different features with quantifiable differences and functionalities that can be compared with one another. From ECOtronics project, available materials from Tampere University, printed conductors were also to be included with embossing guard ideation. Intention of embossed guard for intelligent packaging functions is to guard the function in different phases of packages lifecycle from abrasion, scratching and other physical wear effects. Highest amount of wear, vibration and other physical effects occur in transport phase of a package.

4.2 Development of testing methodology

Plan for this work is to generate ideas, design, manufacture and test a mechanical modification method for packaging material. Designed embossing guards, manufactured tools and manufacturing setup are ready, but choosing and development a suitable testing method was still required. Embossed boxboard guards' main function is to protect intelligent packaging features from wear.

ASTM D5264 – 98 abrasion resistance testing standard presents procedure to determine abrasion resistance for printed materials with Sutherland rub tester. Testing according to this ASTM standard cannot be done without large number of changes to the receptor block size of the machine. The standard specifies also, that the test samples are to be flat without scoring, ridges, or other surface irregularities. Size of standard receptor blocks, where the samples would be fastened are 51 by 178 mm and 51 by 102 mm. (ASTM D5264 2019)

Neither of the above-mentioned points cannot be followed, since embossing samples by nature will not be flat and will have ridges, and the size of embossed features are over the standard receptor block size, another testing method and apparatus will be developed for abrasion testing.

A testing method for wear testing for embossed intelligent packaging feature guards started from defining material requirements and manufacturing methods. Due to the specificity of abrasion testing for these samples, simple design with as few parts and manufacturing steps was planned. Main design was planned to utilize sheet metal parts and aluminium frame. Power source for the abrasion testing machine would be an electric motor. Functional design for the machine would have:

1. Vertically moving surface to produce wear for embossed samples
2. Sample holder where samples are attached and easily removed
3. Rigid frame that is not affected by mechanical force from moving surface

For the finalized machine, 2 mm thick sheet metal parts were used, except a more rigid 3 mm sheet metal was chosen for vertically moving wear surface. The frame for the machine was constructed using of 30 x 30 mm and 30 x 60 mm profile aluminium bars that are sawed to length. In Figure 26 the finalized SolidWorks model of the design is presented. Table 7 describes the functions, materials, and the manufacturing methods of the numbered parts from figures Figure *26* and Figure *27*.

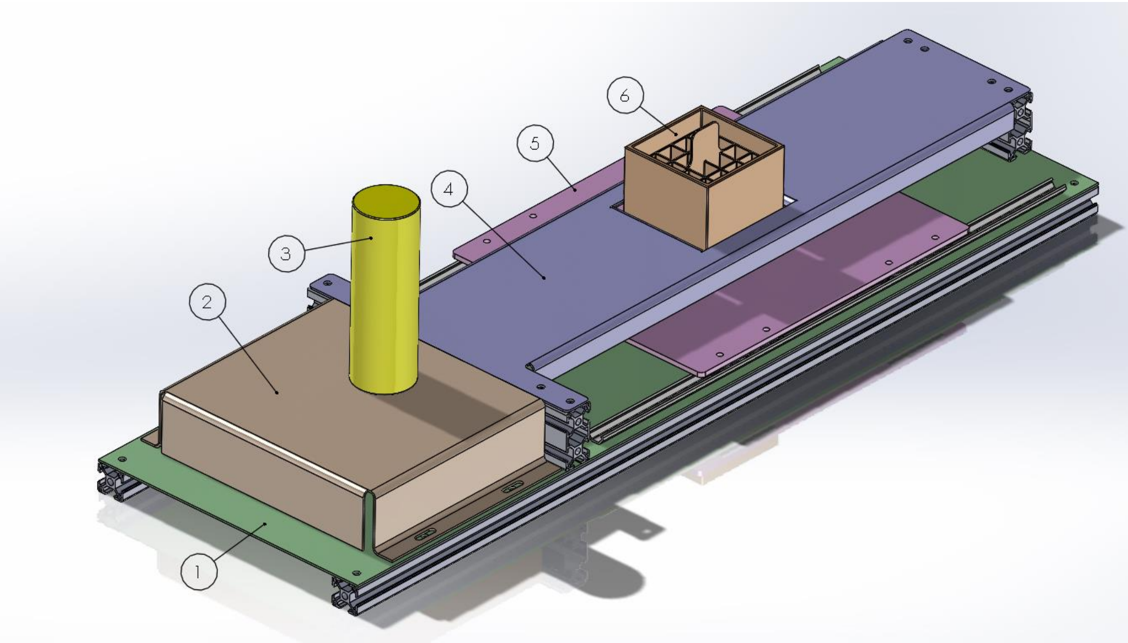


Figure 26. Design of wear testing machine. Colors in model are to illustrate different components of the design. Numbered components are described in Table 7.

In Figure 27. Close-up of electric motor and vertical wear part structure. Numbered items are described in Table 7., a closer look on the working principle of the machine is showed with rail, threaded rod and joint system. Due to the crank design, the wear plate has 200 mm of horizontal movement.

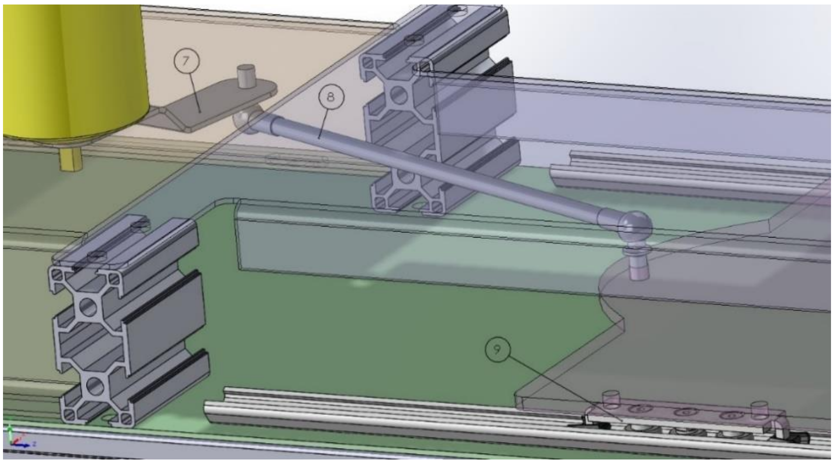


Figure 27. Close-up of electric motor and vertical wear part structure. Numbered items are described in Table 7.

Table 7: Wear testing machine parts with descriptions.

Part number	Description	Material and manufacturing
1	960 x 310 mm base plate.	2 mm sheet metal. Laser cut.
2	Actuator mount. Includes holes for mounting electric motor with bolts and mount to the base plate.	2 mm sheet metal. Laser cut and bended with press brake.
3	Electric motor with gear ratio of 1:68. In figure a placeholder without details.	From manufacturer.
4	Frame to keep testing holder in place. Bended flanges for rigidity.	2 mm sheet metal. Laser cut and bended with press brake.
5	Vertically moving wear plate. Attached to rails and electric motor.	3 mm sheet metal. Laser cut.
6	Packaging sample holder. Has separate secondary part with holder for added weights.	ABS 3D printing filament. 3D printed with Prusa i3 MK3S printer.
7	Crank for electric motor.	2 mm sheet metal. Laser cut and bended with press brake.
8	M8 threaded rod. Fastened to crank and wear plate with angle ball joints.	Stainless steel. Sawed to length.
9	Commercial low friction C-rails. Fastened to wear plate and base plate.	From manufacturer.

The whole construction is fastened together with M6 hex head bolts. Wear testing machine will be computer controlled, and rotation speed of the motor can be numerically set. Embossed samples will be fastened to 100 x 100 x 100 mm 3D-printed sample holder with rubber band or tape, and additional weights can be added to the sample holder. The horizontally moving wear plate will move 200 mm in set direction on low friction rails. Bended flanges on the frame and actuator mount increase safety, safeguarding user from moving parts. Total size of wear testing machine is 960 x 310 x 190 mm. Manufactured and assembled wear testing machine is illustrated in Figure 21 in methods section of this thesis. The size of the machine is suitable for tabletop use.

4.3 Embossed guards for intelligent packaging features

Embossed guards for intelligent packaging features were developed to be manufactured from two commercial boxboard materials, Aegle White 290 and Foodbox 230. The chosen manufacturing method would be hot embossing using Shimadzu-ASG10kNX tension compression machine with heated elements and embossing tooling configuration. The design template for designing embossing tools was already generated as a part of ECOtronics project earlier on, shown in Figure 12. To further develop embossed guards and differentiate functionalities, multiple functions were developed:

1. Two types of stiffened structures around and in intelligent packaging features
2. Larger and wider guarding frames around intelligent packaging features
3. Debossing feature guarding intelligent packaging features under outermost packaging layer

For the printed conductor samples, the same principles of debossing and guarding frames were developed. In Table 8 is listed all developed embossing guards, with corresponding toolset ID numbers and brief explanation of application of embossing tool. Toolset numbers 1 to 4 were developed previously as a part of ECOtronics project.

Table 8: Developed embossing guards.

Embossing and toolset ID	Embossing guard name	Application
Toolset 5	Circular frame	Protection of Stora Enso's Bobbin NFC label
Toolset 6	Rectangular frame	Protection of Stora Enso's ECO Rack RFID label
Toolset 7	Rectangular stiffened frame	Protection and increase of rigidity of Stora Enso's ECO Rack RFID label
Toolset 8	Corrugated oval frame	Protection and increase of rigidity of Stora Enso's ECO Rack RFID label
Toolset 9	Conductor frame	Protection of printed electrical conductor
Toolset 10	Conductor deboss	Deboss to protect printed electrical conductor
Toolset 11	Rectangular deboss	Deboss to protect Stora Enso's ECO Rack RFID label
Toolset 12	Circular deboss	Deboss to protect Stora Enso's Bobbin NFC label

For all embossing and debossing features, distance from guarded feature is always 1.76 mm, which will provide enough room for label insertion. Figure 28 demonstrates NFC and RFID label embossed guard final dimensions. Width of the embossed guard is 2.76 mm wide. Yellow sketch outlines indicate the size of intelligent packaging feature size, NFC label, RFID label, or printed conductor. Function of a wider embossing guard is to increase the rigidity of the guard by increasing the size. With increased rigidity less contact should happen with label and abrasive surface, and the guard itself would withstand higher physical forces. Also, with wider embossing area, possibly deeper and in this case higher embossing guarding could be achieved with more area for deformation for paperboard.

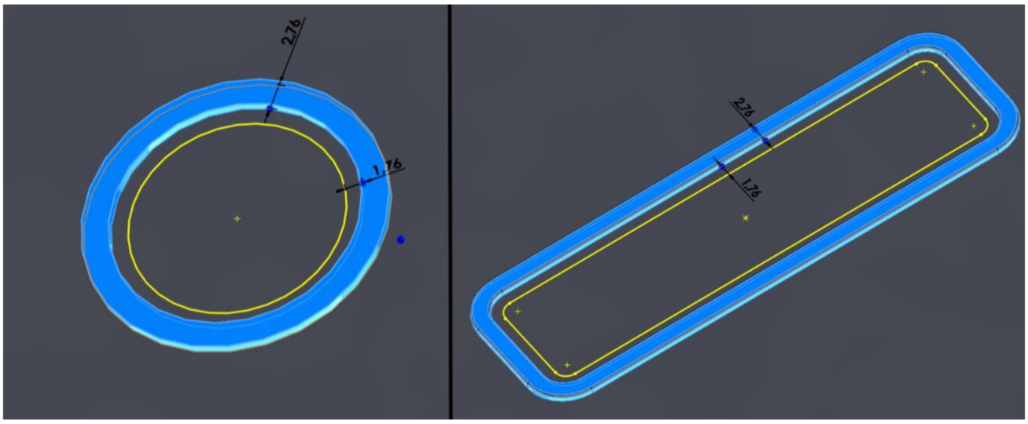


Figure 28. Larger embossed guard frame models for NFC and RFID labels.

Figure 29 illustrates developed embossed guard for printed conductor samples. Width of outer edge of the guard is 1,5 mm. This developed guard is designed to be simple and easy to emboss and locate for printed samples. The guard is intended to protect abrasion of printed metallic conductors, as they could be susceptible to scratching, which could affect resistance and conductivity of the conductors, or outright break them.

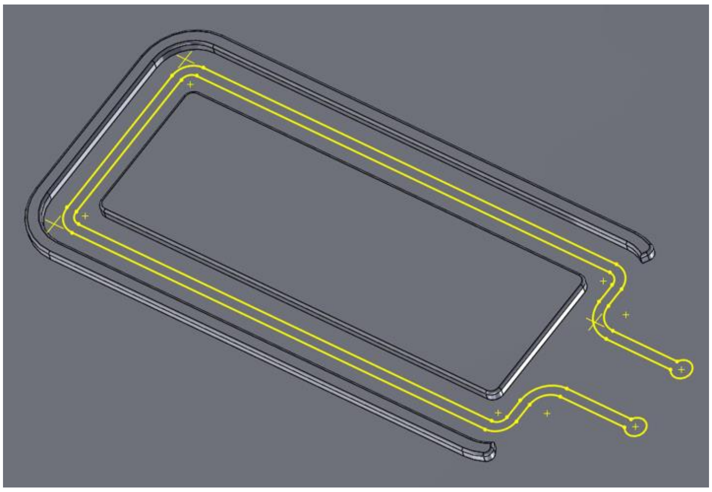


Figure 29. Guard embossing for printed samples.

For more rigid structure with stiffening embossing and debossing is shown in Figure 30. Two different approaches were developed to increase the rigidity of the structure in and around RFID labels. a) in Figure 30 has rigidity increasing stiffeners in the form of a deboss. b) has stiffened oval structure around the label in a large area to increase rigidity and bending stiffness.

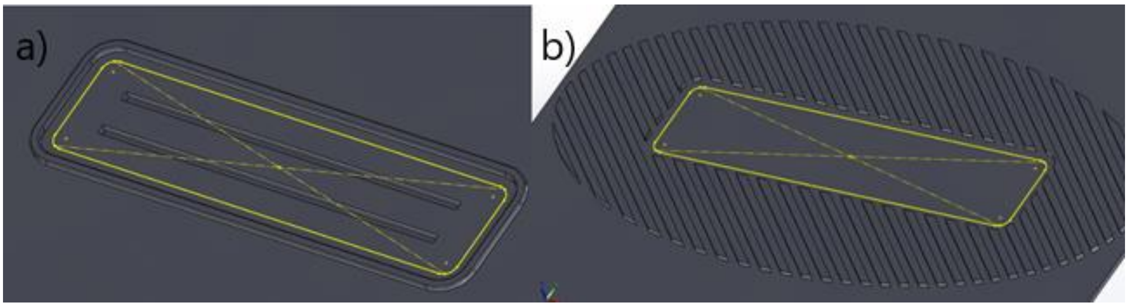


Figure 30. Two different configurations with stiffened features for emboss guarding. a) has stiffeners inside the feature, as b) has larger stiffened frame outside of the feature.

3D models illustrated in figures 28-30 were converted to 2D DXF format files and from there with Inkscape to vector images for manufacturing. Figure 31 illustrates finalized CNC machined brass embossing tools capable of hot embossing. Each toolset is designed with three alignment holes and upper female tools have 4,5 mm holes with insets.

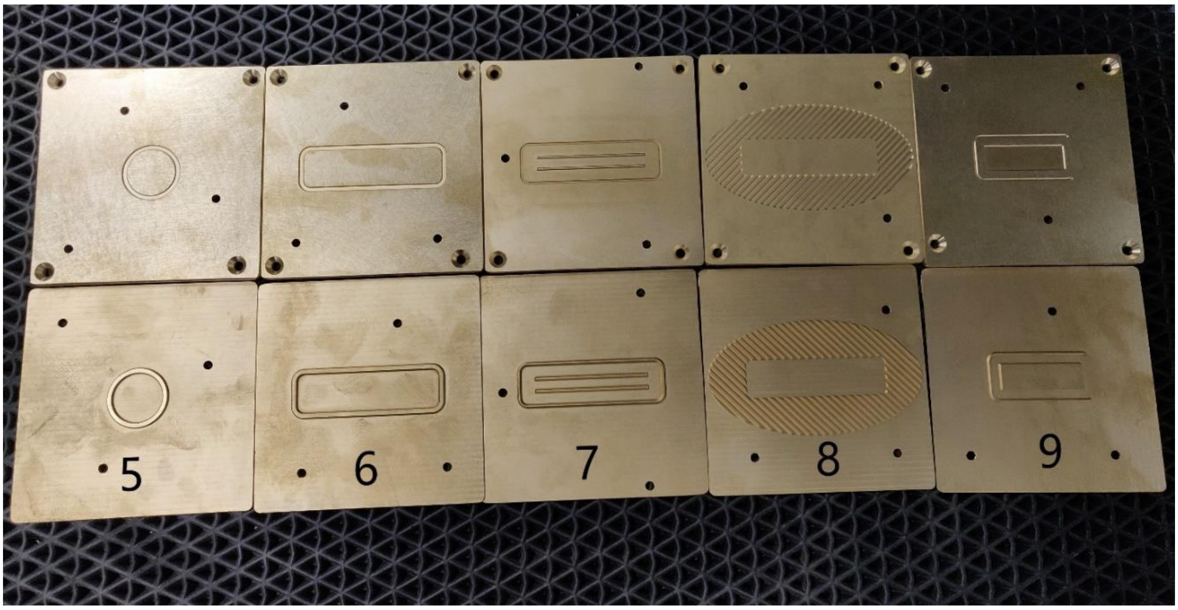


Figure 31. Manufactured brass embossing tools (toolsets 5–9).

Upper female tools, upper tools in Figure 31, are fastened with bolts as lower male tools are fastened to base sheet with glue and tape. This ensures positioning of male tools correctly with help of alignment pins inserted in both female and male tools during alignment.

Tooling for debossed guards was chosen to be manufactured in LUT laboratory, with sheet metal parts. Debossing tools from 1 mm thick stainless-steel sheet were designed. Female debossing tools would have intelligent packaging feature holes, that would form the outer edge of the deboss. Female tools would be fastened to a base plate with bolts, and male tools would be fastened to base sheet similarly with brass embossing tools. Male tools are 1,76 mm wider from the edge of the intelligent packaging features, for same distance from the features than already designed embossing tools. Figure 32 shows manufactured laser cut sheet metal tools.

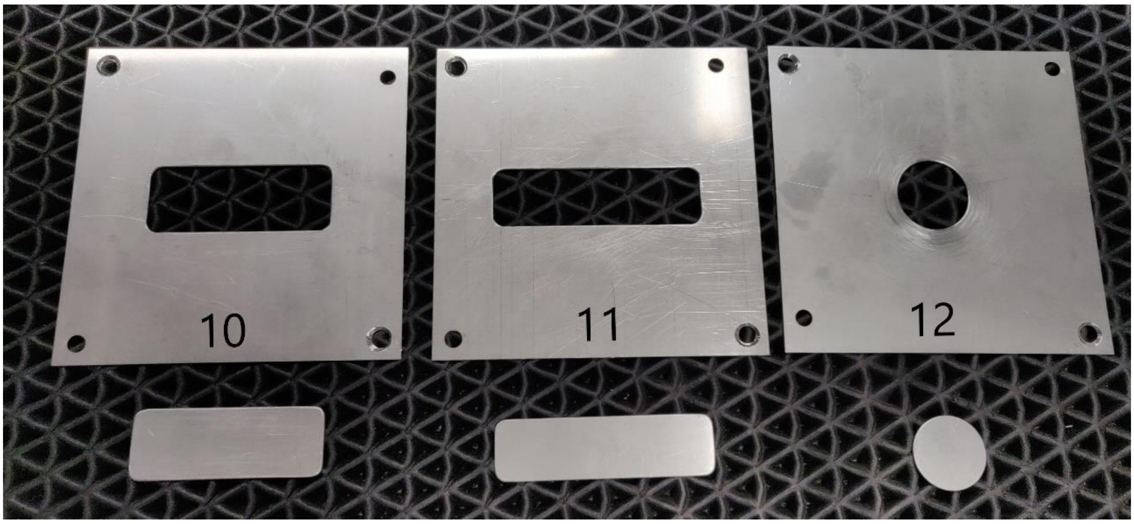


Figure 32. Sheet metal tools for debossed guards (toolsets 10–12).

Postprocessing for the sheet metal tools included grinding and sanding of edges of the tools to have fillet radius of approximately 0.5 mm for the embossing edges. Thickness of the sheet metal provides naturally depth for the deboss.

4.5 Test results

Embossing and wear testing was completed successfully. Results on embossing profile heights, label readings and resistances were gathered. Due to the difficulty of positioning the conductor samples, embossing was successful only approximately 70% of the time.

Topographical measurements with profilometer were taken for corresponding samples of different materials at same positions for comparable results. Figure 33 illustrates measures on conductor frames. Same principal procedure was conducted on all samples. Reported height measurements for before and after wear testing are presented in tables Table *9* andTa-ble *10*.

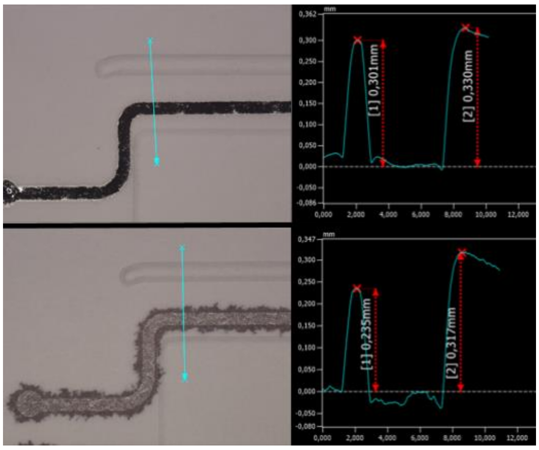


Figure 33. Profilometer measurements of printed conductor frames.

Debossing depth is presented as positive figure for comparability of results. Aegle White 290 average height reduction for guards was 0,02 mm from the wear testing. For Foodbox 230, wear testing in average reduced height of guards by 0,04 mm.

Table 9: Aegle White 290 embossing sample wear test results. Changes in depth are re-ported.

Aegle White 290	Emboss depth before wear testing (mm)	Emboss depth after wear testing (mm)
Rectangular frame with project logo (TOOLSET 3)	0.116	0.108
Circular frame with project logo (TOOLSET 4)	0.189	0.171
Circular frame (TOOLSET 5)	0.330	0.29
Rectangular frame (TOOLSET 6)	0.417	0.38
Rectangular stiffened frame (TOOLSET 7)	0.332	0.311
Corrugated oval frame (TOOLSET 8)	0.124	0.083
Conductor frame (TOOLSET 9)	0.301	0.33
Conductor deboss (TOOLSET 10)	0.405	0.356
Rectangular deboss (TOOLSET 11)	0.370	0.376

Circular deboss (TOOLSET 12)	0.545	0.532

Even though average height reduction was larger in Foodbox guards, reverse visual effect is noticeable. Aegle White samples have noticeable polishing effect at peaks of the guards. Foodbox samples have little or no noticeable visual changes from wear testing. This can be speculated to be from difference in top layer of boxboard construction compared to Aegle White, even though in friction measurements Foodbox had higher kinetic friction coefficient compared to Aegle White. All embossed samples before wear testing are presented in appendix 1, and after wear testing in appendix 2.

Table 10: Foodbox 230 embossing sample wear test results. Changes in depth are reported.

Foodbox 230	Emboss height before wear testing (mm)	Emboss height after wear testing (mm)
Rectangular frame with project logo (TOOLSET 3)	0.121	0.100
Circular frame with project logo (TOOLSET 4)	0.128	0.106
Circular frame (TOOLSET 5)	0.386	0.28
Rectangular frame (TOOLSET 6)	0.481	0.435
Rectangular stiffened frame (TOOLSET 7)	0.205	0.162
Corrugated oval frame (TOOLSET 8)	0.047	0.04
Conductor frame (TOOLSET 9)	0.235	0.226
Conductor deboss (TOOLSET 10)	0.341	0.306
Rectangular deboss (TOOLSET 11)	0.395	0.338
Circular deboss (TOOLSET 12)	0.419	0.361

Resistance measurements from all test phases for printed conductors on Aegle White are presented in Figure 34. Same resistance measurements for Foodbox conductor samples are presented in Figure 35. Because of the scarcity of Foodbox printed samples, resistance measurements are averaged from 2 samples on both figures for comparability. As can be seen, resistance was affected by embossing and wear testing.

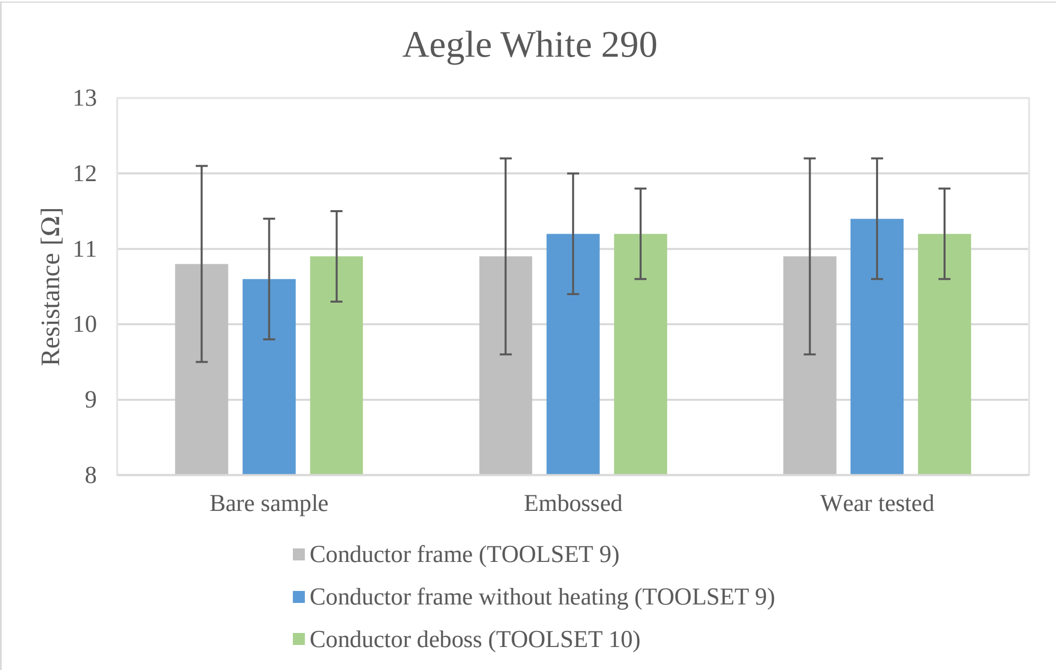


Figure 34. Resistance measurements of printed conductor samples on Aegle White substrate.

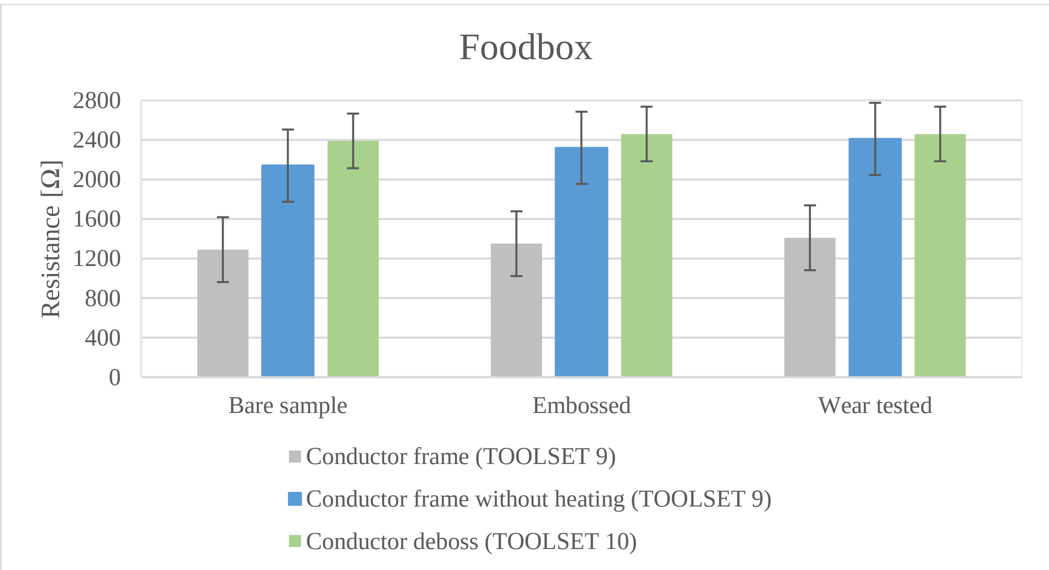


Figure 35. Resistance measurements of printed conductor samples on Foodbox substrate.

In Figure 36 rectangular emboss frames are compared to non-heated embossing, and heated samples with storage RH 80% embossing. From the figure can be seen, that regular 80 °C heated embossing sample in atmospheric humidity has the largest emboss height.

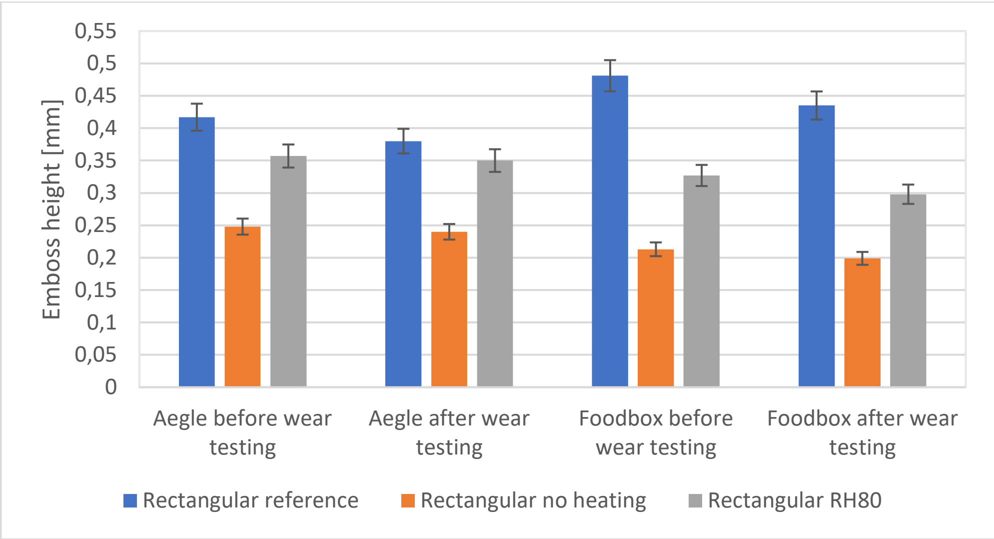


Figure 36. Height comparison of reference, no heating and RH80 of rectangular frame emboss.

In Figure 37 conductor frames are compared between reference and non-heated embossing samples. Height difference is more significant on Aegle White samples, compared to Foodbox samples.

From manufacturing perspective, using hot embossing instead of embossing with no heating might not be necessary, even though there is a difference in emboss profile height. Added step of higher RH storing did not increase emboss profile height positively, but with Foodbox samples, it did decrease some wrinkling at the corners of the emboss. From an industrial perspective, maintaining packaging material at increased moisture content seems like a large undertaking, so only in rare occasions could it be considered.

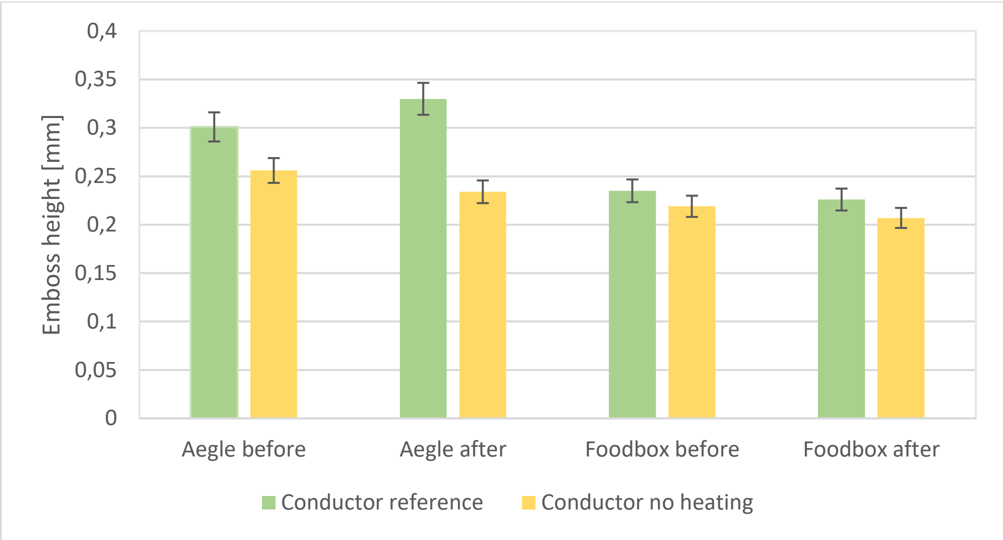


Figure 37. Height comparison of conductor reference and no heating samples.

Resistance of Aegle White samples was increased 3,1% from embossing on average, and from wear testing only 0,60%. For Foodbox samples, embossing increased resistances on average by 7,8%, and wear testing by 1,6%. Wear testing yielded visual differences on Aegle White conductors. This is illustrated in Figure 38. Printed conductor without embossing has noticeable scratching all around the conductor. Emboss guarded conductor has much less scratching, but polishing effect can faintly be seen at the guards. Resistance without embossed guards on average increased by 1,3% from wear testing on Aegle White samples and 1,5% for Food box samples.

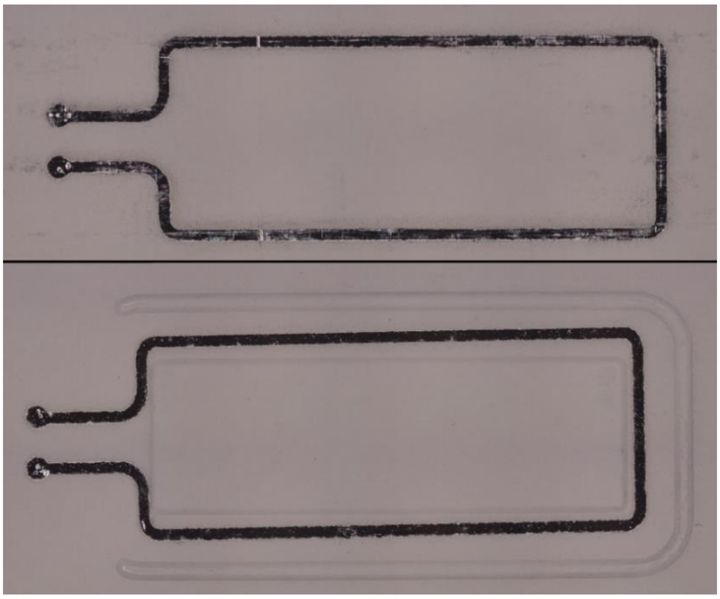


Figure 38. Printed conductor after wear testing. Above image is without guard and below with guard.

Figure 39 illustrates wear resistance difference of RFID label with and without guards. On label without guards, minor scratching and breakage can be seen at the edge of the label, which is not present on label with guards.

Figure 39. RFID label after wear testing. Left image is without guard right image is with guard.

All NFC labels were readable before and after wear testing. RFID distance readings are presented in appendix 3. Distances varied from 12 to 17 meters. Wear testing had no negative effect of reading distance.

Test samples against steel wear plate experienced heavy staining from the plate. In appendix 4 are presented results of wear test against wear plate. Total staining was lesser with embossed guards. Staining was concentrated at the highest points of the guards, instead of evenly spreading out, like with samples without guarding.

SEM imaging for Aegle White rectangular frame is presented in Figure 40, Foodbox circular frame in Figure 41, and bare conductor sample after wear testing against steel plate in Figure 42. In Figure 40, darkened area is the polishing effect from wear testing, now more noticeable than with the naked eye. The same darkening can be seen on the reference sample without wear testing, but to a much lesser degree.

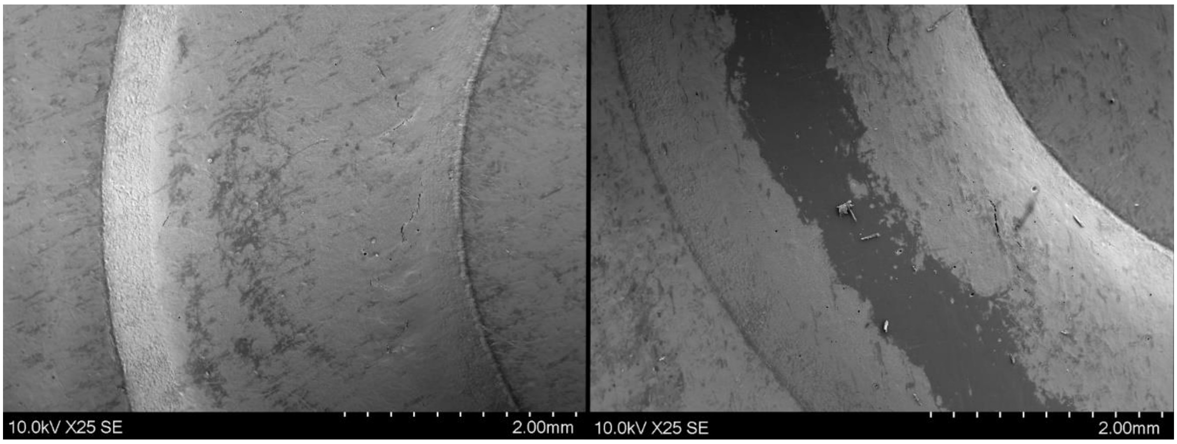


Figure 40. Aegle White rectangular frame SEM images. Left image is before wear testing and right image is after.

Foodbox embossed samples experienced much fewer visual alterations from wear testing than Aegle White samples, when inspected with the naked eye. In Figure 41, is a magnification of emboss area minor tearing can be seen in the fibers on left image, which is not present in same extent on the right, non-tested image.

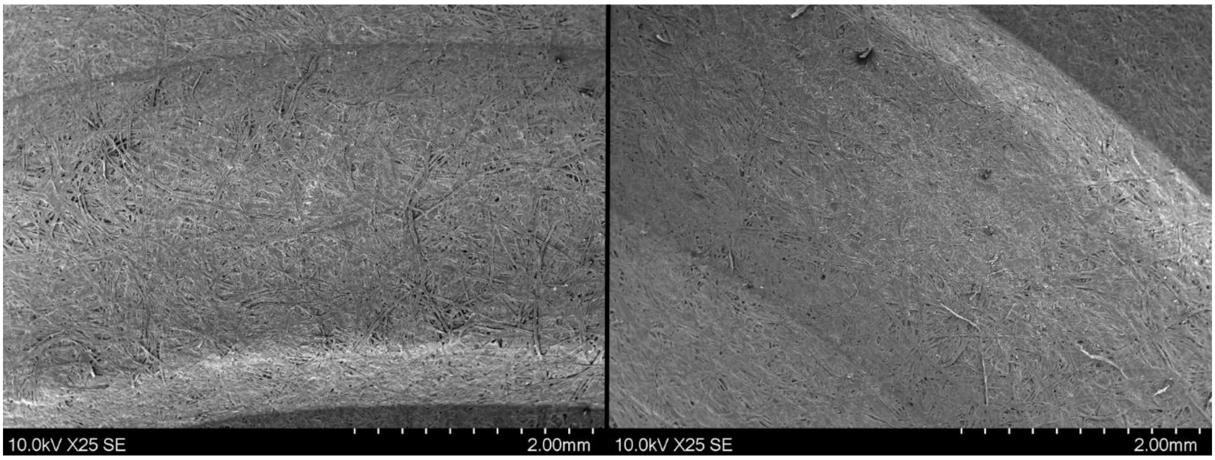


Figure 41. Foodbox circular frame SEM images. Left image is before and right image is after wear testing.

Printed conductors on Aegle White samples were scratched heavily on the surface. In Figure 42 scratched and stained close-up of Aegle White conductor sample without embossing is presented. Wear testing scratch and darker staining can be seen on the surface of the conductor, and some tearing on the edges of the conductor can be seen. The conductor doesn’t seem to have any deeper than surface damage.

Overall, visual inspection and topographical and SEM image data showed differences, especially between non-embossed samples and embossed samples. Differentiation between each embossed guard is a harder task to quantify.

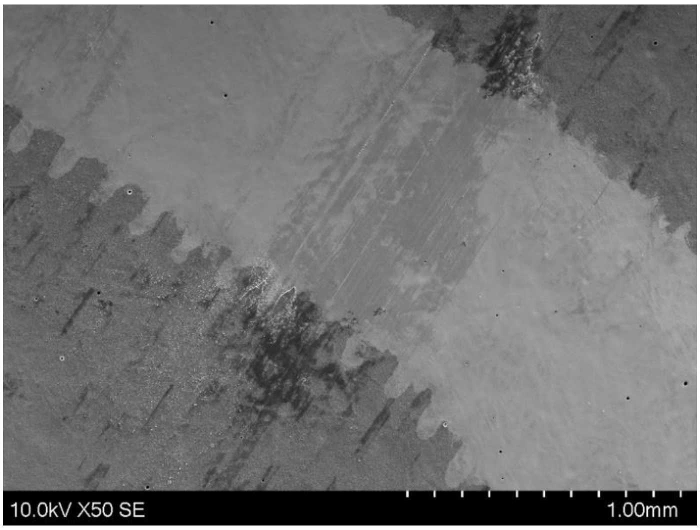


Figure 42. Printed conductor on Aegle White substrate after wear testing against steel plate.

5 Conclusions

This thesis consists of literature review on intelligent packaging and multiple package manufacturing methods. Also, food packaging is covered slightly because its prevalence in the field of packaging. A pool of ideas was generated through idea creation process, with basis in mostly theoretical state-of-the-art studies, but also in commercial packaging innovation sources.

From 13 ideas, one was developed further. Embossed guarding frames for intelligent packaging features were developed with different guarding principles. Wider guard frames, two stiffening solutions and debossing solutions were designed. Guarded features were rectangular RFID labels, circular NFC labels and printed conductors on boxboard substrates. Guarded frames were embossed on Aegle White 290 and Foodbox 230 boxboard materials. A testing procedure and wear testing machine were developed specifically for emboss guard wear testing. Wear testing, label read measurements and resistance measurements from conductors were conducted. Label readability was not affected from wear testing for NFC nor RFID. Conductor resistances were only slightly affected, and more from embossing compared to wear testing. With visual inspection, noticeable positive differences were noticed on embossed samples. Especially on Aegle White substrate, embossed guards protected conductors and to some extend labels from scratches. Foodbox samples were less visually affected from wear testing, but had higher decrease in emboss height.

Developed embossed guards were effective in their designed function. Since readability of intelligent labels and resistance readings from conductors didn’t widely get affected by wear testing, no strong recommendation can be given only on that basis for embossed guards. Embossed guards however had positive effect on visual quality around and on labels and especially Aegle White conductors. If conductors were printed with fewer layers and with thinner lines, wear could affect resistances and other functionality much more, which would justify embossed guarding for functional reasons. Manufacturing costs could be justified on higher end packaging and high-end products. For food packaging or other low-cost packaging, embossed guards for their manufacturing time and cost cannot yet be justified if done separately. However, if embossing was to be integrated to the die cutting process together with cutting and creasing, the cost and time could be justified. Embossed protecting frames and other solutions for intelligent packaging features should be considered, especially when more sensitive components and elements are used. No large functional difference between different embossed guard structures were found based on test results. Based on this result, different emboss guards can be utilized in different type of packaging designs. Other applications for embossed guards could be printed intelligent elements, such as barcodes and QR-codes.

Further research could be done studying and trying different wear testing parameters, speeds, time, and added weight. This could provide important insights. Further research in embossing guards, and other emboss features with TTIs and other intelligent packaging features should be conducted. Transportation and other stress package must endure can be mitigated through packaging material modifications. For wider innovation in packaging structure modification, only the sky is the limit.

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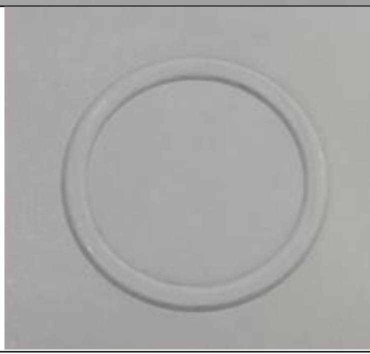
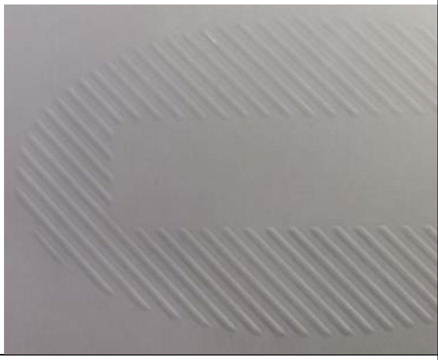
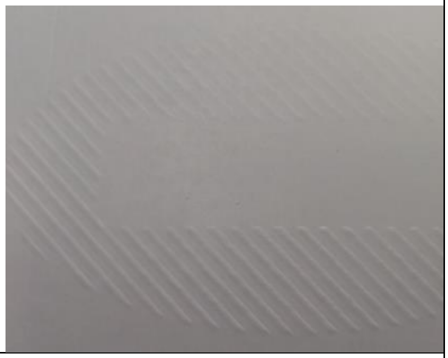
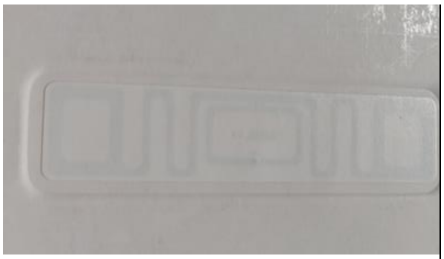
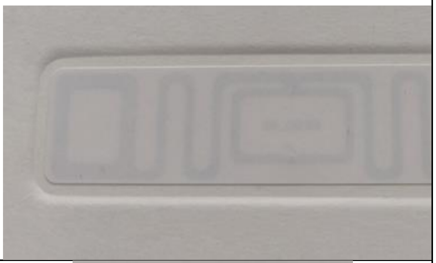
Appendix 1. Embossed guards before wear testing

	Aegle White 290	Foodbox 230
Rectangular frame with project logo		
Circular frame with pro-ject logo		
Circular frame		
Rectangular frame		
Rectangular stiffened frame		

Corrugated oval frame		
Rectangular deboss		
Circular deboss		

Appendix 2. Embossed guards after wear testing.

	Aegle White 290	Foodbox 230
Rectangular frame with project logo		
Circular frame with pro-ject logo		
Circular frame		
Rectangular frame		
Rectangular stiffened frame		
Corrugated oval frame		

Rectangular deboss		
Circular deboss		

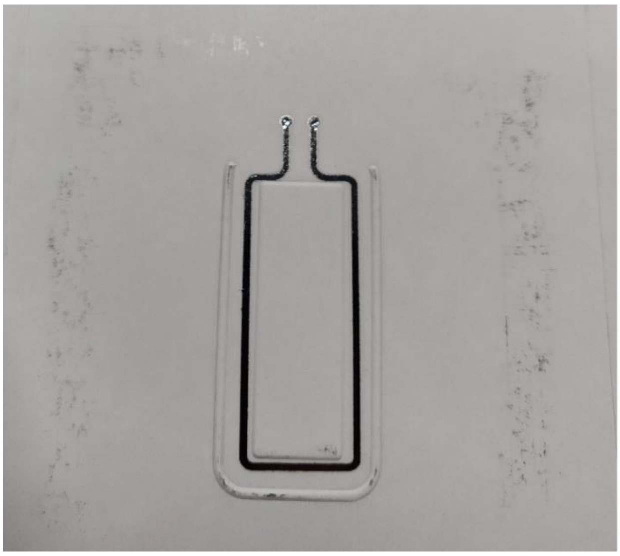
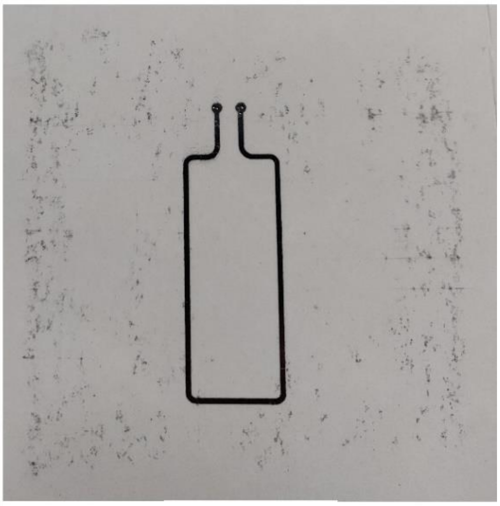
Appendix 3. RFID label read distances.

Aegle White 290	Read distance before wear testing (m)	Read distance after wear testing (m)
Rectangular frame	12.3	13.2
Rectangular frame without heating	16.1	16.1
Rectangular frame - RH 80%	15.6	13.7
Rectangular stiffened frame	16.9	17.1
Corrugated oval frame	17.6	17.5
Rectangular deboss	15.6	15.3

Foodbox 230	Read distance before wear testing (m)	Read distance after wear testing (m)
Rectangular frame	15.1	16.1
Rectangular frame without heating	14.9	15.5
Rectangular frame - RH 80%	12.1	16.2
Rectangular stiffened frame	15.0	13.8
Corrugated oval frame	15.6	14.4
Rectangular deboss	15.8	16.1

Appendix 4. Wear test results against steel wear plate.

Aegle White samples:

Foodbox samples: