Lappeenranta
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PRESS FORMING OF PAPERBOARD – ADVANCEMENT OF CONVERTING TOOLS AND PROCESS CONTROL

Thesis for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in the Auditorium 1382 at Lappeenranta University of Technology, Lappeenranta, Finland on the 14th of December, 2015, at noon.

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ABSTRACT

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Press forming is nowadays one of the most common industrial methods in use for producing deeper trays from paperboard. Demands for material properties like recyclability and sustainability have increased also in the packaging industry, but there are still limitations related to the formability of paperboard. A majority of recent studies have focused on material development, but the potential of the package manufacturing process can also be improved by the development of tooling and process control.

In this study, advanced converting tools (die cutting tools and the press forming mould) are created for production scale paperboard tray manufacturing. Also monitoring methods that enable the production of paperboard trays with enhanced quality, and can be utilized in process control are developed.

The principles for tray blank preparation, including creasing pattern and die cutting tool design are introduced. The mould heating arrangement and determination of mould clearance are investigated to improve the quality of the press formed trays. The effect of the spring back of the tray walls on the tray dimensions can be managed by adjusting the heat-related process parameters and estimating it at the mould design stage. This enables production speed optimization as the process parameters can be adjusted more freely. Real-time monitoring of pressing force by using multiple force sensors embedded in the mould structure can be utilized in the evaluation of material characteristics on a modified production machinery.

Comprehensive process control can be achieved with a combination of measurement of the outer dimensions of the trays and pressing force monitoring. The control method enables detection of defects and tracking changes in the material properties. The optimized converting tools provide a basis for effective operation of the control system.

Keywords: press forming, die cutting, converting tools, paperboard, packaging, monitoring, process control

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Lappeenranta, December 2015

Panu Tanninen

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Publications

List of publications and the author's contribution

The thesis is based on the following Papers, which are referred to in the text by Roman numerals.

I Tanninen, P., Kasurinen, M., Eskelinen, H., Varis, J., Lindell, H., Leminen, V., Matthews, S., and Kainusalmi, M. (2014). The effect of tool heating arrangement on fibre material forming, Journal of Materials Processing Technology 214(8): 1576-1582

II Leminen, V., Tanninen, P., Mäkelä, P., and Varis, J. (2013). Combined effect of paperboard thickness and mould clearance in the press forming process, BioResources 8(4): 5701-5714

III Tanninen, P., Lindell, H., Saukkonen, E., and Backfolk, K. (2014). Thermal and mechanical durability of starch-based dual polymer coatings in the press forming of paperboard, Packaging Technology and Science 27(5): 353-363

IV Tanninen, P., Saukkonen, E., Leminen, V., Lindell, H., and Backfolk, K. (2015). Adjusting the die cutting process and tools for biopolymer dispersion coated paperboards, Nordic Pulp & Paper Research Journal 30(3): 335-342

V Tanninen, P., Leminen, V., Eskelinen, H., Lindell, H., and Varis, J. (2015). Controlling the folding of the blank in paperboard tray press forming, BioResources 10(3): 5191-5202

VI Tanninen, P., Leminen, V., Kainusalmi, M., and Varis, J. (2016). Effect of process parameter variation on the dimensions of press formed paperboard trays, BioResources 11(1): 140-158

VII Tanninen, P., Matthews, S., Ovaska, S., Varis, J., and Backfolk, K. (2015). A novel technique for the evaluation of paperboard performance in press-forming, *Submitted to Journal of Materials Processing Technology*

The author was responsible for designing the converting tests in all Papers and participated in the implementation of the experiments. The author also participated in analyzing the results, drawing conclusions and was one of two main manuscript writers in all Papers. In Papers I, IV, VI and VII the author was one of the two designers of the tooling setups that were presented in the Papers and used in the experiments.

SUPPORTING PUBLICATIONS

1. Leminen, V., Kainusalmi, M., Tanninen, P., Lohtander, M., and Varis, J. (2012). Effect of Sealing Temperature to Required Sealing Time in Heat Sealing Process of a Paperboard Tray. Journal of Applied Packaging Research 6(2): 67-78

2. Leminen, V., Tanninen, P., Lindell, H., and Varis, J. (2015). Effect of blank holding force on the gas tightness of paperboard trays manufactured by the press forming process. Bioresources 10(2): 2235-2243

3. Leminen, V., Mäkelä, P., Tanninen, P., and Varis, J. (2015). Methods for Analyzing the Structure of Creases in Heat Sealed Paperboard Packages. Journal of Applied Packaging Research 7(1): 49-60

4. Leminen, V., Mäkelä, P., Tanninen, P., and Varis, J. (2015). The use of chromatic white light 3D-profilometry in the surface quality analysis of press-formed paperboard trays Proceedings of the 25th Flexible Automation and Intelligent Manufacturing, FAIM2015, Volume II, pp.74-81. Wolverhampton, UK: The Choir Press.

ABBREVIATIONS AND SYMBOLS

3D	Three-dimensional
c	Creasing coefficient
CD	Cross Direction
C_{dmin}	Distance between adjacent Creasing grooves (centerline to centerline)
d	Forming Depth
D_{CG}	Depth of Creasing Groove
DT	Destructive Testing method
F_{BH}	Blank Holding Force
F_N	Normal Force to blank holding force
F_p	Pressing Force
$F_{\mu 1}/F_{\mu 2}$	Friction Forces
GN	Gastronorm
MAP	Modified Atmosphere Packaging
MD	Machine Direction
PE	Polyethylene
PET	Polyethylene Terephthalate
r_1/r_2	Radiuses of crease sets
r_{BC}	Radius of Blank Corner
R_{CR}	Radius of Creasing Rule tip
SBS	Solid Bleached Sulphate
SEM	Scanning Electron Microscope
T_1	Temperature of the female mould
T_2	Temperature of the male mould
T_{PB}	Thickness of Paperboard
W_{CG}	Creasing Groove Width
W_{CR}	Creasing Rule Width
W_{ML}	Width of the Land between adjacent creasing grooves

x	Distance between folding edges
α	Angle of substrate transfer
μ_1/μ_2	Coefficients of friction

1. Introduction

1.1 Background

Environmental values are topical issues in the manufacturing industry at the moment, and demands for material properties like recyclability and sustainability have increased also in the packaging industry. The environmental perspective on packages emphasizes the use of materials of non-oil-based origin. Regarding consumer packages, the food sector is an area where a change in policy may generate the highest impact.

Plastic is the most versatile material for producing 3D packages and providing good barrier properties. However, fibre-based materials have desirable properties like biodegradability, recyclability, good printability, "green" image, and renewability (Vishtal and Retulainen 2012). To utilize the benefits of both materials, composite structures are frequently used to reduce the amount of plastic needed and to provide the needed barrier properties for the packages.

Rhim (2010) states that among the four basic packaging materials of paper, plastics, glass and metals, paper is the most widely used packaging material for food and non-food products in the form of bags, wrappings, cups, boxes, folding cartons, composite cans, corrugated fibreboard boxes, and fibre drums, used not only in primary packaging but also in secondary or tertiary packaging.

Currently trays with internal volume and dimensions used in retail are usually produced of plastic film by using a thermoforming process. The thermoforming process can be utilized also with paperboard, but the depth of the acquired trays is not sufficient for most food packaging applications, due to the limited formability of paperboard in comparison to plastic. Press forming is a more suitable paperboard converting technique for producing deeper paperboard trays. However, the conversion of a fibre-based material into a 3D package is a complex process. Thus, there is an urgent need to understand the means by which the forming of 3D packages from fibre-based materials can be improved. The base substrate and the barrier coating layer must withstand the converting process. The development of the packaging solutions should thus consider both the development of the packaging material and the tools used in converting. A number of recent studies have focused on material development (Huang and Nygårds 2012; Larsson et al. 2014; Post et al. 2011; Svensson et al. 2013; Östlund et al.2011; Vishtal and Retulainen 2014a and 2014b; Vishtal et al. 2015), but the potential of the package manufacturing process can also be improved by the development of tooling.

The runnability and efficiency of the production process is usually evaluated by analysing the quality of the end product. Material properties of the formed substrate, e.g. paperboard, are measured comprehensively in laboratory conditions before and after converting, and some of the properties are likely to change during the forming process.

Consequently, monitoring methods that provide real-time data of paperboard tray production and more thorough understanding of the phenomena related to press forming and forming tool-substrate interaction are needed. The monitoring methods enable more efficient use of the substrate and the tool combination during production runs.

1.2 Objectives of the thesis

The first objective of the thesis was to develop converting tools advancing the production scale paperboard tray manufacturing.

The second objective was to develop monitoring methods enabling the production of paperboard trays with enhanced quality which could be utilized in process control.

1.3 Hypotheses

The experimental approaches and theoretical aspects used in this study are based on following hypotheses:

- Quality of the press formed trays can be enhanced with improvements related to the tray blank preparation. Geometry of the die cutting tool and creasing pattern can be modified for this purpose.

- During the press forming process, mould features affecting directly to the paperboard blank, i.e. mould heating and mould geometry, play a key role in improving the quality of formed products. In this respect, the implementation of the mould heating arrangement and the mould clearance can provide significant advancements.

- Data required for a sophisticated control of press forming process can be achieved by measuring the forming process and the end product. Measuring methods and related devices can be designed to be integrated to the converting equipment.

1.4 Scope of the thesis

The thesis concentrates on the press forming process of paperboard, which is divided into four sections, as shown on Figure 1. When all the sections are fully optimized, the process control has a stable basis for successful production. The roman numerals labelled in each section indicate which Papers are related to the subject matter.

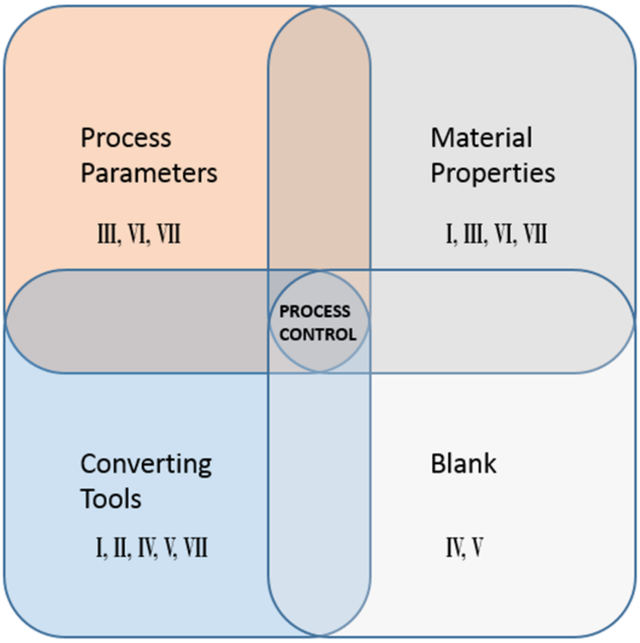

Figure 1: Press forming process of paperboard, division into four sections and related Papers.

The work is primarily limited to converting tool development and press forming process control. The process control part discusses the requirements for successful controlling, whereas the control system structure and algorithms have been excluded from the work. The investigation of material properties is limited to a few essential properties, although some of the summarised Papers have more extensive research in this context. Also package design is outside the scope of this work.

1.5 Outline

Chapter 2 is a comprehensive introduction to the press forming process including a comparison to other forming processes and an analysis of forming forces.

Chapter 3 presents the converting equipment used in the experiments and the converted substrates.

In chapter 4, the results of the tests are introduced and discussed.

Chapter 5 presents conclusions of the work.

2. Press forming of paperboard

Today, a majority of commercial trays representing retail volume and dimensions are produced of plastic film by using a thermoforming process. Thermoforming utilizes primarily heat and vacuum in forming, but also compressed air and a mechanical punch can be used to assist the process. The thermoforming process can be used also with paperboard, but the depth of the acquired trays is not sufficient for most food packaging applications. Shallow trays produced with this method are used for packing cheeses, vegetables, cold cuts etc.

Press forming (also referred to as tray pressing and stamping) and folding are the most common methods for producing deeper trays from paperboard in industrial use. Folded trays are produced in the same manner as cardboard boxes, and the method cannot therefore be classified as forming. Both these methods utilize creases to achieve the desired tray shape. In press forming creases are used to guide the folding in the tray corners when the blank slides into the mould cavity.

During the folding process, creasing lines with plastic deformation allow the blank to fold accurately and easily without cracking of the board structure (Joukio and Mansikkamäki 1998). The creases are positioned according to the faces of the folded tray, and during the folding phase, the seams of the tray blank are usually glued together.

The use of creases during press forming is much more complex. The geometry of a press formed tray does not contain clear faces, and the shape of a tray corner is rounded and consists of multiple folds. Creases are used to control the blank forming process. The blank is folded regularly, and the plastic coating of the paperboard blank seals adjacent creases together during the press forming process. Forces that are parallel and perpendicular to the blank plane cause folding in the corner area; thus, creases are used to control how folding occurs. The differences in the use of creases can be seen in Figure 2.

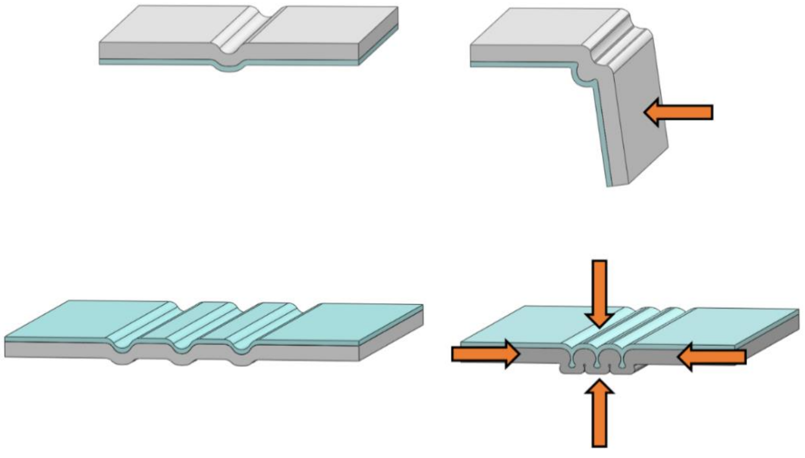

Figure 2: The behaviour of creases in folding (above) and in press forming (below). In these methods, creasing is performed on different sides of the substrate to retain the polymer barrier layer inside the package.

Trays or plates of smaller depths can also be produced from blanks without creases. A ready-made tray and a creased blank are presented in Figure 3.

Figure 3: Press formed paperboard tray on top of the tray blank.

A variant of press forming adds injection moulding to the process, and the flange of the tray is produced from plastic. Another variant of press forming is hot pressing (Kunnari et al. 2007), in which the blank is fixed and the forming is based on elongation of the formed substrate. Other forming methods have been developed, like deep-drawing

(Hauptmann and Majschak 2011) and hydroforming (Groche et al. 2012), but they are not widely used in industrial applications.

2.1 Process parameters and tools in press forming

The basic principle of the press forming of trays is to place a pre-cut and creased, possibly polymer-coated paperboard blank between male (MM) and female moulds (FM). The male mould presses (pressing force, blue arrows) the blank into the mould cavity of the female mould and a tray of a desired shape is formed, as shown in Figure 4. The folding of the tray corners is controlled with the blank holding force (orange arrows), applied by a rim tool (RT). Blank holding force restrains the sliding of the blank into the mould cavity, which enables operation of the creases.

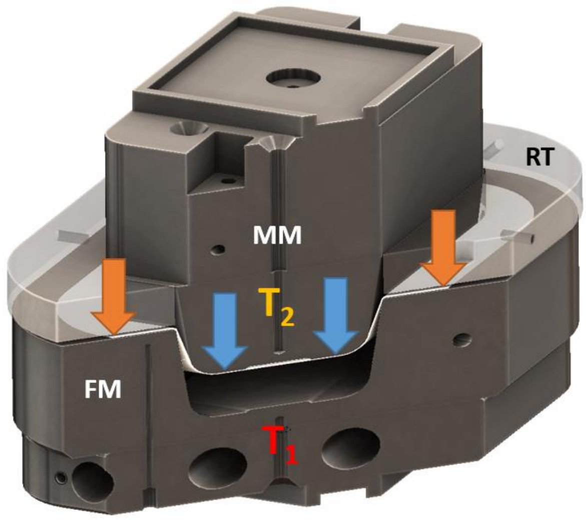

Figure 4: Press forming mould set and forming forces.

The male mould is held at the bottom end of the stroke for a set time (dwell time) while the polymer coating softens, and adjacent creases in the corners of the tray are sealed together. Simultaneously the flange of the tray is flattened by a greater force, also applied by the rim tool. Finally, the formed tray is removed and a new blank is fed into the tray press. The ready-made tray achieves its final rigidity when it cools down. The female mould is heated (T_1) to improve the formability of the formed substrates (Salmen 1993), while the male mould is kept at a lower temperature (T_2). Greater heat is applied only to the uncoated side of the material in order to prevent melting of the polymer coating. In addition to the above-mentioned process parameters, also pressing speed, the velocity of the male mould until it is stopped by the female mould, is one of the main parameters. Pressing speed and mould geometry determine the speed of blank sliding. Die-cutting of a blank is usually carried out so that the longer side of the blank is parallel to machine direction (MD) of the paperboard to give the ready-made trays more rigidity.

2.2 Tray quality and defects

The quality of the paperboard tray can be considered good when the tray dimensions are accurate and the creases in the tray corners are folded and formed evenly. The sealing area in the tray flange is smooth and planar. Naturally, there are no fractures, wrinkles or other defects in the tray walls.

The quality of the tray is important for several reasons, such as visual appearance as well as the gas-tightness of modified atmosphere packaging and thus the microbiological safety of the packaged product. Dimensional accuracy of packages is a prerequisite for the operation of the production and supply chain. Package size affects the operation of the filling and lidding machinery, the stacking of packages in transport boxes, and the fluency of retail operations.

The surface quality of the sealing area is critical for an air-tight seal when the package is sealed with a lid. The most severe deformation happens in the corners, and it is therefore the area most likely to have defects that cause leaks in the package. Heat-sealed tray-shaped packages are widely used with modified atmosphere packaging (MAP). However, MAP is not widely used with plastic-coated press formed paperboard packages in tray form because of the challenges associated with package tightness. Sealing the lid is a critical step in MAP, as the sealing process and the quality of the seal can affect the production rate and shelf life. In addition to preventing the package from leaking, the seal must also prohibit air from coming in contact with the food (Yeh et al. 1997).

Typical defects that can emerge in press formed paperboard trays are:

- Dimensional inaccuracy of trays is the most common defect in paperboard trays, generated by incorrect adjustment of process parameters. Also stacking of the trays can change the tray dimensions.

- Deformed creases are not formed properly, and the corresponding folds have large gaps in the tray flange area, which makes tight lidding of the tray impossible.

- Ruptures (fractures, cracks) are generated when the material cannot withstand the forces it is exposed to. The strength properties of the material are insufficient for the used process setup.

- Wrinkles are folds that are not assisted by creases. They can be caused by a too small blank holding force or an incorrectly designed creasing pattern. Wrinkles emerge usually in areas that are not creased, which has an effect on the overall visual quality of the package.

- Sticking of the polymer coating to the mould surface occurs when too high mould temperatures are used, and in consequence the substrate sometimes ruptures. Even minor sticking makes material transfer more difficult and ready-made trays can be damaged. Sticking also leaves marks into the coating surface of the paperboard that are at least visual defects, and pinholes can emerge on the coating surface.

- Blistering of the polymer coating occurs when the softened coating layer detaches the paperboard, usually due to vaporized water. Excessive humidity content of the substrate or too high mould temperature can cause the symptom.

- Pinholes are very small holes in the coating layer that ruin package tightness. Pinholes can be generated in the coating process or the converting process.

- Wear in the print surface is due to the fact that the used ink (or varnish) does not endure the abrasion exerted by the mould surfaces, or high temperature.

When press forming production is within the process window, wrinkles and fractures are not probable defects. Dimensional inaccuracy and wear in the print surface are more likely to cause actions.

2.3 Selected material properties

Although the material properties have been excluded from the scope of this thesis, some of them are briefly discussed in this chapter, because they are essential in the press forming process.

Formability, convertibility and runnability are commonly used terms in the context of paperboard press forming. The formability of a material can be described simply as the level (amount of strain) to which that material can be deformed (stretched) before fracture occurs (Emmens 2011), or as a complex mechanical property that determines the performance of a material in the forming process. Formability depends on several mechanical properties related to the aspects of formability: elongation, compressive strain, compressive strength, and substrate-to-metal friction (Vishtal and Retulainen 2012). The formability of the material is insufficient in relation to the tool geometry or process parameters when defects emerge.

Convertibility is a property that is also affected by equipment-related features - paperboard with good convertibility possesses good folding, creasing or scoring properties (Cavlin 1988). Runnability describes how substrates perform in press forming, for example how dimensional stability/accuracy is maintained, how material transfer functions, or whether loose particles become detached from the surface of the substrate.

Temperature and moisture both have an effect on the elastic modulus of paperboard. The elastic modulus decreases when the temperature is raised and/or the moisture content increased (Ghaderi and Golzar 2009, Salmen and Back 1980). The fibre structure of the paperboard is softened and the material becomes more formable. A raised mould temperature improves the formability of the paperboard but also has an effect on the rate of evaporation of the moisture content. Condensed vapour on the tool surface affects the friction between the blank and the tool surface. Controlling the moisture content is essential in the press forming of paperboard. The initial moisture content of the paperboard can be maintained or changed by storing the materials in a humidity-controlled chamber. The moisture content is usually 8-10% before the converting stage.

Spring back is a shape change associated with re-establishing equilibrium after external forces have been removed (Östlund et al. 2011). Spring back is a well-known phenomenon in various forming processes which use wood-based materials. Spring back is a heat-dependent phenomenon (Golzar and Ghaderi 2009, Hauptmann and Majschak 2011), and the dimensional accuracy of press formed paperboard trays is dependent on the amount of spring back.

3. Materials and Methods

All converting tests were carried out by using the Adjustable Packaging Line developed by the Packaging Laboratory of Lappeenranta University of Technology (LUT) for research work related to packaging and packaging material development (ERDF 2008). The Packaging Line includes a flatbed-diecutter and a press forming unit, which both are extensively adjustable in terms of process parameters. The tested substrates were stored in a humidity-controlled chamber to obtain the equilibrium moisture content for each material, which was verified before converting phases with a moisture analyser.

3.1 Test substrates

The substrates used in the converting tests are listed in Table 1. More detailed information about the substrates can be found in Papers I-VII.

Table 1: Test substrates in Papers I-VII.

Paper	**Baseboard structure**	**Polymer coating**	**Grammage [gsm]**	**Material name in the Paper**
I	Three solid bleached sulphate (SBS) layers	PET- extrusion coating	350 + 40	
II	Three solid bleached sulphate (SBS) layers	PET- extrusion coating	190 + 40 230 + 40 310 + 40 350 + 40	
III	Three solid bleached sulphate (SBS) layers, top-side mineral coated	Starch-based dual polymer dispersion coatings	210 + (0.9 – 14.6)	Materials 1-12
IV	Three solid bleached sulphate (SBS) layers, top-side mineral coated	Starch-based dual polymer dispersion coatings	210 + 14.3 210 + 15.7	Material 1 Material 2
		Synthetic polyolefin dispersion coating	210 + 7.7	Material 3
		PE - extrusion coating	210 + 22.6	Material 4
V	Three solid bleached sulphate (SBS) layers	PET- extrusion coating	350 + 40	
VI	Three solid bleached sulphate (SBS) layers	PET- extrusion coating	350 + 40	

VII	Three solid bleached sulphate (SBS) layers	PET- extrusion coating	350 + 40	Material 1
	Three solid bleached sulphate (SBS) layers, top-side triple pigment coated, reverse side single coated	PE - extrusion coating	240 + 20	Material 2
	Solid bleached board + 5 gsm PE + Board + PE coating 60 gsm		300 + 65	Material 3
	Solid bleached board + vegetable parcel laminate		390 + 40	Material 4

The primary test substrate was a solid bleached sulphate (SBS) paperboard, which is the substrate commonly used in tray manufacturing and consists typically of three layers. A polyethylene terephthalate (PET) coating provides good barrier properties, and has good thermal stability and suitable forming properties for press forming. The converting tests performed in Paper IV were repeated with PET-coated samples, which gave similar results as polyethylene (PE) -coated samples.

3.2 Tray blank preparation

Tray manufacturing consists of two stages: die cutting of tray blanks and press forming of blanks into ready-made trays. In the establishment phase of the press forming process, tool design and tool materials were considered in relation to the substrate to be converted. Factors affecting the die cutting tool and the creasing pattern design were studied (Papers IV and V).

3.2.1 Die cutting tool

The convertibility of different biopolymer dispersion coated and PE-coated paperboards was studied in Paper IV by using creasing tools with various geometries. Paper IV clarified critical steps in the mechanical converting of biopolymer dispersion coated paperboard packaging substrates, concentrating especially on the die-cutting and creasing processes.

Paperboard tray manufacturing was chosen as the testing process due to the possibility of enhancing the forming phase by pre-made creases in the blank. Creases guide the folding of the paperboard blank at the corners of the tray walls, and the requirements for the creasing operation are strict. A large number of creases in a single tray blank enables extensive barrier testing with a limited amount of samples.

The main dimensions of the creasing rule and groove are presented in Figure 5.

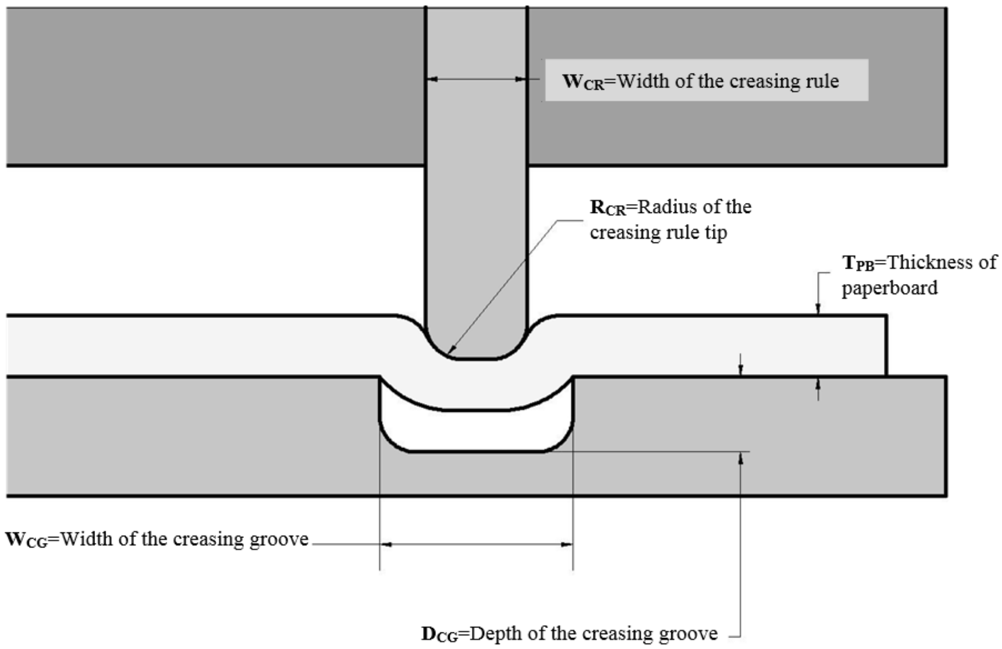

Figure 5: The main dimensions of the creasing rule and groove.

All materials were press formed with constant process parameters to obtain comparable results for the convertibility evaluation of the materials. The process parameters were determined in preliminary tests.

The creasing rule profiles were chosen according to the instructions provided by different die cutting tool and paperboard manufacturers. The same creasing pattern of the blank, which functionality was confirmed in preliminary tests, was used with all tool sets, with the focus on the geometry of creasing grooves.

Die cutting tool manufacturers offered two basic types of creasing grooves - straight and conical groove walls. Both of these were selected to the die cutting tests. The width of the rule was chosen as 0.71 mm (2 pt rule, according to the naming practice used by the tool manufacturers), and the depth of the creasing groove as 0.5 mm. The groove widths can be calculated to fit the corresponding creasing rules by using the following formula

$$W_{CG} = c\, T_{PB} + W_{CR} \tag{1}$$

where W_{CG} is the creasing groove width, c is the creasing coefficient, T_{PB} is the thickness of the paperboard, and W_{CR} is the creasing rule width (see Figure 5).

Instructions provide values ranging from 1.2 to 1.8 for coefficient *c*, depending on the material to be processed. In preliminary tests, the creases were converted with a set of creasing grooves manufactured with coefficient values 1.1 – 2.0. The narrowest grooves caused incision-like fractures and tearing of the paperboard, and with the widest grooves the formation of the crease was deficient/insufficient. Therefore, in this study the paperboard was die-cut with coefficient values between 1.4-1.7.

Die cutting tools were designed, and six sets of tools were acquired from two tool manufacturers. The toolsets installed in the flatbed diecutter are presented in Figure 6.

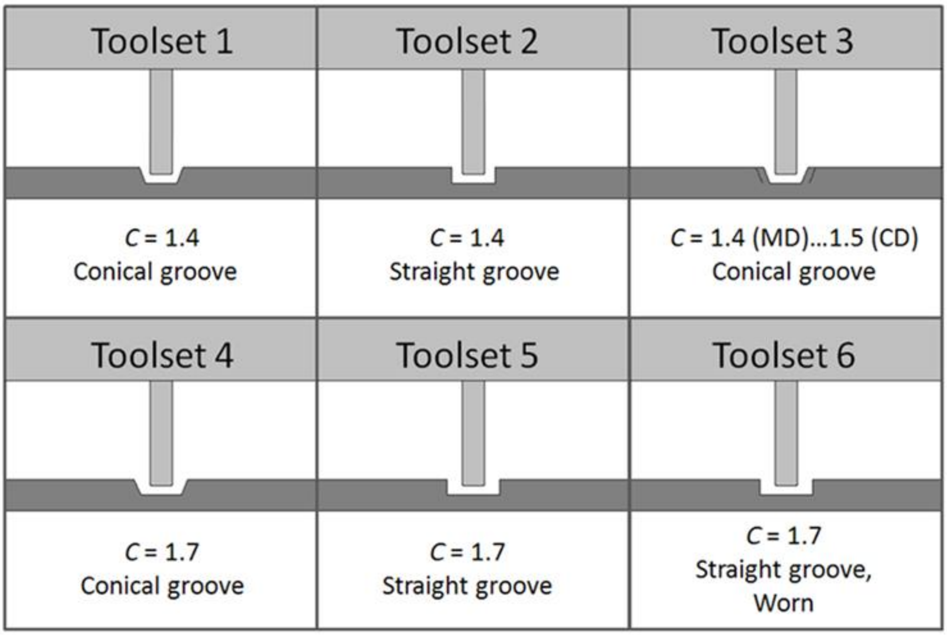

Figure 6: Creasing rule profiles used in the convertibility tests. Creasing coefficient *c* defines the creasing groove width in relation to the substrate thickness.

The groove width was selected for toolsets 1 and 2 by using the value 1.4 which represents a rather tight creasing process. In toolset 3, the groove width was similar to toolsets 1 and 2 in machine direction (MD) but widened in cross direction (CD) with a coefficient of 1.5. Varying the groove width was used to balance the operation of the creases, as the stiffness of the paperboard is lower in CD than in MD (Kirwan 2005).

A *c* value of 1.7 was used with toolsets 4 and 5 with the purpose of reducing the stresses in the biopolymer coating. All counter dies were made of similar tool grade steel to ensure dimensional accuracy and constant surface roughness. Toolset 6 was similar to toolset 5, but it had been previously used for approx. 100 000 punches and the edges of the creasing tools were clearly rounded. Any failure of the tool was not detected and the type of wear can be considered typical for a tool that has been used a lot. Toolsets 2, 5 and 6 had straight groove walls, whereas toolsets 1, 3 and 4 had conical groove walls to smoothen the shape of the creases.

An evaluation of the structure of the creases was performed after the die cutting and again after press forming. This provided information about the origin and creation of the different defects found in ready-made packages. Microscope imaging of resin-embedded cross-sections of the tray corners clarified the effects of mechanical and physical stresses further. Samples of tray blank corners were cast in acryl plastic to preserve the shape of the creases during the processing. After grinding and polishing, the samples were analysed. The integrity of the biopolymer barrier coating was analysed by applying a colouring solution (dyed ethanol) onto the coating surface. The liquid was spread on the coated paper and allowed to penetrate for 5 min. The colouring solution dyes the fibre structure of the paperboard through pinholes and the number of pinholes can be counted.

In Paper V, a selection of commercial creasing rules with different widths was acquired to study the effect of the creasing rule width. Paperboard manufacturers recommend the use of creasing rules with the width of 0.71 mm (2 pt.) for testing the thickness of a substrate. Also, rules with the widths of 0.40 mm (1.1 pt.), 1.05 mm (3 pt.), and 1.42 mm (4 pt.) were tested. The purpose of these tests was to study how material compaction and folding occurred in the tray corner area when the width of the creases was altered, in order to determine if a single, wider crease could compact more material.

3.2.2 Blank design

Factors affecting the folding process of a press formed tray corner were studied in Paper V, and the basic principles for creasing pattern design were developed. The design of a creasing pattern includes the positioning of creases and determination of the amount and dimensions of creases.

A selection of commercial paperboard trays was collected from the European region, and the geometry of the trays, including the positioning of creases, was analysed to form a view on the current practices in the packaging industry. Three different methods for creasing pattern design were found on the evaluated trays, presented in Figure 7. In all methods, the placement of creases correlates to the radii of the tray corners.

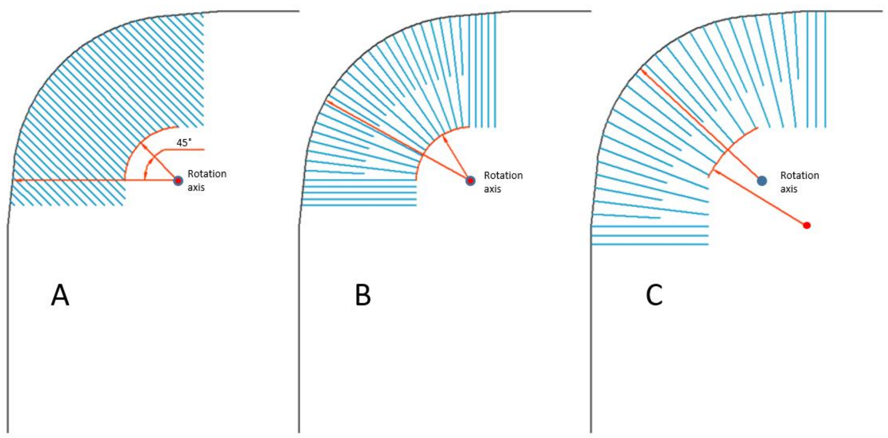

Figure 7: Creasing pattern designs. A) Creases are positioned at a 45° angle in relation to the sides of the blank, parallel to each other; B) creases are positioned radially toward the rotation axis of the tray corner; C) creases are positioned radially toward a point deviating 10 to 30 mm from the rotation axis of the tray corner.

Several creasing patterns using methods A, B, and C were tested preliminarily, and it was found that the patterns using method B facilitated the folding of the paperboard blank in the most favourable manner. Trays that were produced by methods A and B had significantly more partially folded creases, especially in the ends of the creasing sector. Therefore, in all further tests, the creases were positioned according to method B - radially and toward the rotation axis of the tray corner.

The compilation of creasing patterns was studied by producing blanks with different creasing patterns. The blanks were press formed into ready-made trays, and the quality of folding and material compaction was analysed. An array of industrial-scale press forming tool sets was selected with the basic shape of the tray corner in mind. The tool sets enabled the production of trays representing four different rectangular designs and one oval-shaped design. Even though the main dimensions of the trays varied, the main focus was on the dimensions related to the tray corner area: the depth of the tray and the corner radii.

The creases were positioned uniformly to the corner area of the tray blank and radially toward the rotation axis of the tray corner. The composition and essential dimensions of the creasing pattern design are shown in Figure 8.

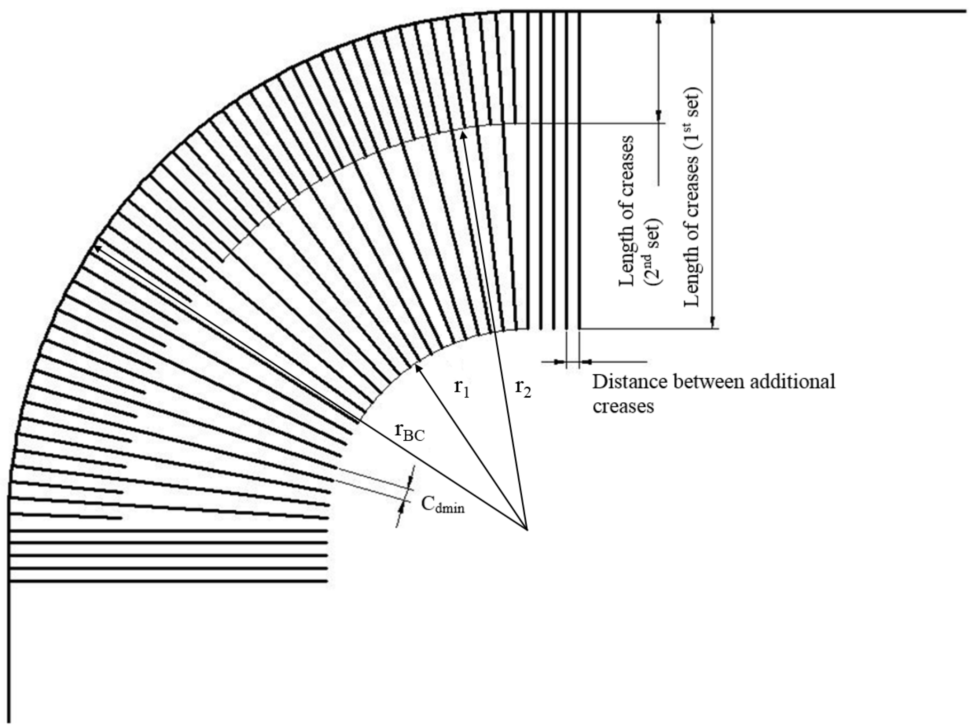

Figure 8: The composition and essential dimensions of creasing. C_{dmin} denotes the minimum distance between creases, r_1/r_2 denote the radiuses of crease sets and r_{BC} denotes the radius of the blank corner.

The width of the land between adjacent creasing grooves was changed within the range of 0.5 to 3.0 mm. The respective number of creases, calculated on the basis of distance values, are listed in Table 2, along with the dimensions of the trays produced. The depths of the trays enabled the use of two sets of creases with different lengths in the corner area.

Table 2: Test tray specifications.

	Tray 1 Rectangular	**Tray 2** Rectangular	**Tray 3** Rectangular	**Tray 4** Rectangular	**Tray 5** Oval
Height of the Tray (mm)	50	35	38	56	45
Length of the Tray (mm)	209	209	265	326	219
Width of the Tray (mm)	139	139	162	261	130
Radius of the Tray Corner (mm)	37	40	40	75.5	65
Length of the Blank (mm)	288	260	319	400	286
Width of the Blank (mm)	219	190	216	334	199.5
Radius of the Blank Corner, r_{BC} (mm)	77	62	70	110	99.25
Radius of the first crease set, r_1 (mm)	20	20	19	37	48
Width of the land between adjacent creasing grooves, W_{ML} (mm)	Total number of creases	Total number of creases	Total number of creases	Total number of creases	Total number of creases
0.5	164	164	157	279	177
1	135	135	129	226	142
1.5	116	116	112	191	120
2	103	103	99	167	104
2.5	93	93	90	149	92
3	86	86	83	135	83

The press forming process parameters were optimized in preliminary tests for tested paperboard to achieve trays of good quality. Differences in the sizes of the trays were compensated for by adjusting the blank holding force (0.81 kN for Trays 1 and 2, 1.20 kN for Tray 3, 2.38 kN for Tray 4 and 0.79 kN for Tray 5). The other parameters were kept constant during the trial runs: female mould temperature 170°C, male mould temperature 50°C, pressing force 135 kN and pressing speed 130 mm/s.

3.3 Press forming tool development

Development of the press forming tool was discussed in Papers I and II. The effect of the tool heating arrangement was studied in Paper I, and the effect of the mould clearance in Paper II.

3.3.1 Heating arrangement of the press forming tool

Mould temperature control is an essential part of managing the forming process and a prerequisite for successful tray manufacturing. The maximum temperature and moisture content of the paperboard blank are typically limited by the material properties of the plastic coating. However, the temperature of the moulds should be as high and even as possible to improve the formability of the paperboard, and therefore the mould heating arrangement is in a critical role in achieving the required temperature throughout the paperboard blank.

The process of paperboard tray press forming has been known for decades, but there are still both functional and structural defects in mould design. The reduction of these defects was pursued in Paper I, concentrating especially on improving mould temperature control and the resulting tray quality. Also simplification of the mould structure from the viewpoint of manufacturing was focused on.

In current press forming moulds, heating is typically accomplished by installing heating elements of various shapes and sizes. These heating elements must fit the machined cavities or bores in the mould precisely. This causes limitations to the mould design due to the manufacturability of these shapes. To produce uniform heat distribution, there must be a number of heating elements of appropriate size.

To reveal their temperature distribution, thermographic images were taken of typical moulds used for press forming. In addition, the functionality and physical structure of the tools were evaluated based on the quality of the trays moulded. Most of the examined tools were rectangular, which is the predominant geometry today. The tooling design developed for this study was also based on a rectangular geometry. Figure 9 presents the thermographic image of a heated female mould with internal bar-shaped electrical elements. The heating elements are symmetrically spaced at 80 mm on either side of the mould centreline (top and bottom in the figure). As the orange colour illustrates, the temperature of the tool surface near the heating elements is relatively high. In contrast, the temperature around the tool centreline is relatively low.

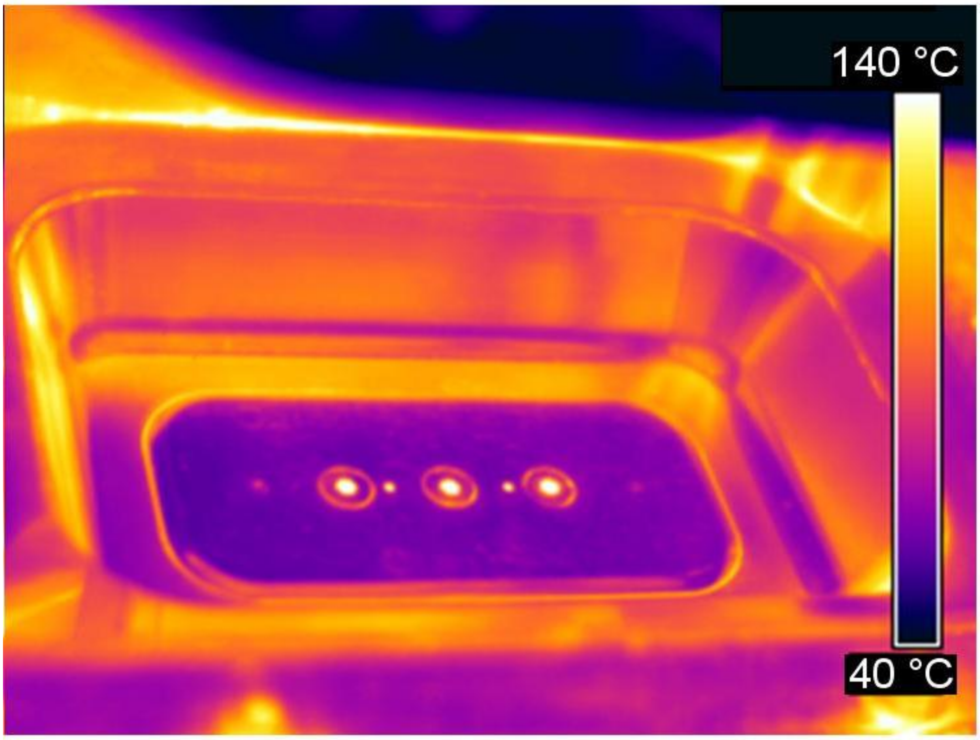

Figure 9: Uneven heat distribution - Typical example of difference in temperature depending on distance to heating elements.

Typically, there is only one temperature sensor imbedded in the mould to provide temperature feedback to the controller. Proper positioning of this sensor is critical for effective thermal process control. In production, each tray that is formed removes heat energy. The thermal control system must replace the lost heat as quickly as it is practical to maintain the set point process temperature. To evaluate the effectiveness of the thermal control system with the temperature feedback of the internal mould temperature sensor, sample short production runs of 35 trays were made with the traditional tray press mould.

Thermographic images were taken of the moulds immediately before and after each production run, and results showed that the mould surface temperature dropped by 18˚C.

Several tray-pressing moulds typical of those being used currently in production were analysed. The observations of this analysis suggested that a new approach to mould design could result in improved tray quality. A new mould was designed, fabricated and evaluated, and the paperboard trays produced by the new mould were carefully inspected to verify the production performance of the mould.

3.3.2 Mould clearance of the press forming tool

The forming process involves a combination of material and tool properties. The effect of paperboard thickness and mould clearance on the final product of the press forming process was studied in Paper II. Various thicknesses of extrusion-coated paperboard were tested and the creases were analysed after the press forming stage to optimize the mould clearance.

The used creasing pattern represents a typical layout in the tray pressing process. The target was to obtain evenly folded creases in the smooth tray walls and the flat flanges of the tray. The ratio of mould clearance and thickness of the paperboard also has a significant effect on the appearance of the tray wall. The mould clearance, which is the distance between the forming surfaces of the male and female moulds, cannot be adjusted during production runs; therefore, the selection of clearance is a critical phase of the mould design process. The behaviour of the paperboard blank was observed in different parts of the mould cavity, as presented in Figure 10.

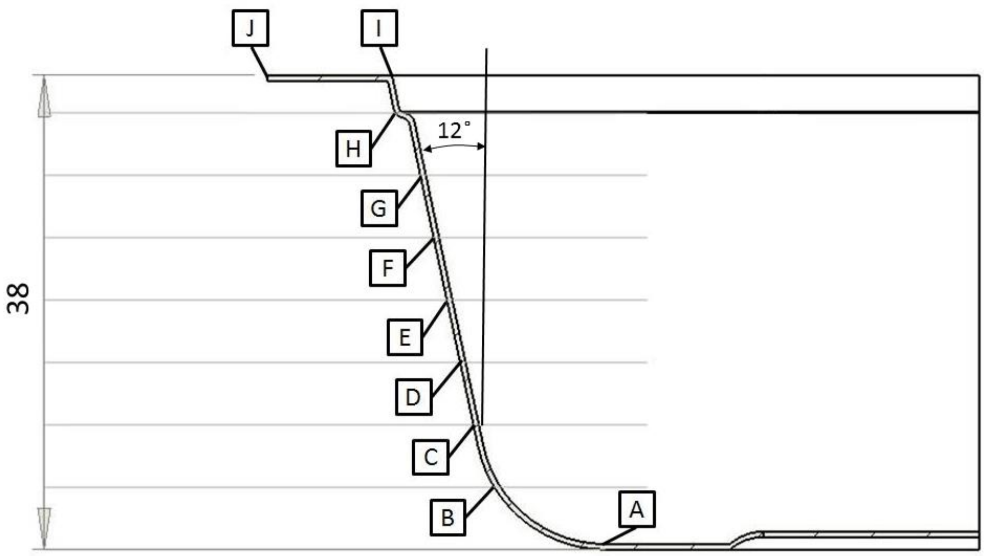

Figure 10: Observation points of the tray corner. The tray walls were analysed from multiple heights with 5 mm intervals. The angle of the tray wall (12º) is relatively steep in relation to the height of the tray.

The length of compressed paperboard in the ready-made tray was compared to its original length at the blank stage. At each observation point, the length of the tray wall tracing arc was compared to its original length, and the ratio of material reduction was calculated. At point I, the required material reduction is largest; therefore, the material has to endure the greatest amount of forming. The usage of mould clearance describes the portion of the mould cavity that is filled with paperboard. If the usage is over 100%, then the paperboard has to compress and contract primarily in-plane. Because the pressing force forms the fibre structure permanently, the irreversible part of the compaction deformation of the paperboard blank in tray pressing can be considered plastic deformation. The surface smoothness of the tray and the quality of the folding of the tray wall in the corners was analysed to determine suitable mould clearances. The quality of ready-made trays was graded according to the scale presented in Table 3. Examples of corners of the tray evaluated with different grades can be seen in Figure 11.

Table 3: Grading scale of the tray wall quality.

Grade	**Description of the tray wall quality**	**Cause**
-2	Creases fold irregularly	Mould clearance too large
-1	Unaccomplished crease smoothening	Mould clearance a bit too large
0	Creases perfectly smoothed	Mould clearance ideal
+1	Tray wall starts to polish too much	Mould clearance a bit too small
+2	Substrate compaction and the forces applied to the material may cause fractures	Mould clearance too small

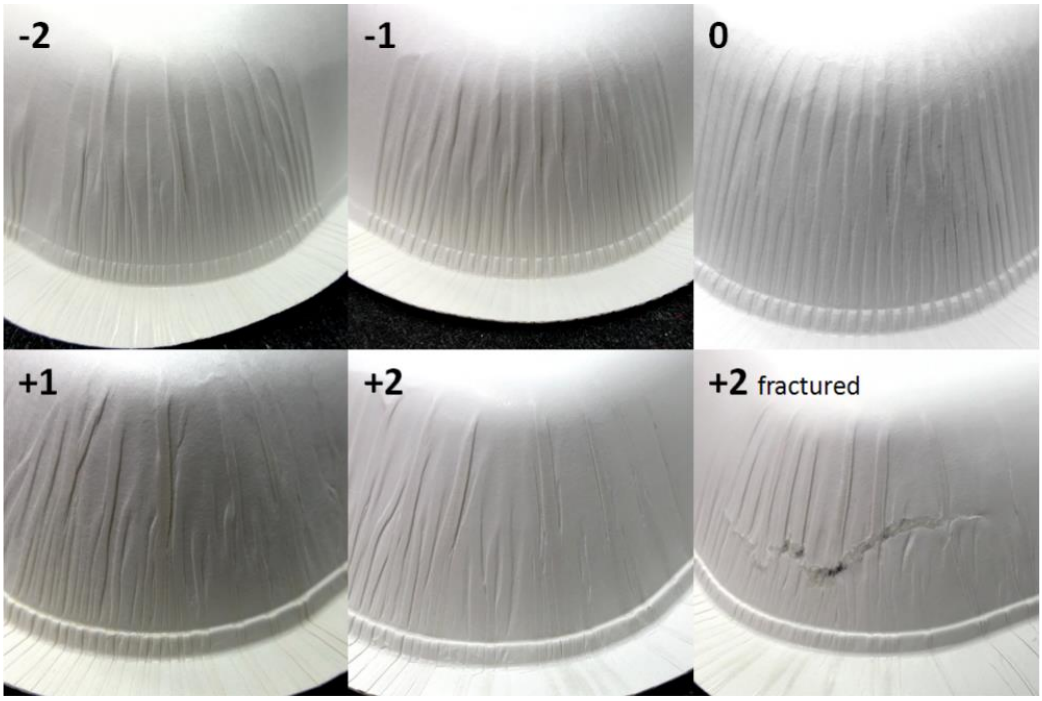

Figure 11: An example of grades of corner quality at observation point D (presented in Figure 10) on the basis of Table 3. Grade 0 is the most desirable one.

Grade 0 is targeted at when the process parameters of tray production are adjusted. Grades -1 and +1 are mainly visual defects; the functionality of the tray is not compromised. However, these grades indicate the direction where the paperboard thickness or the mould clearance should be altered.

The process parameters of tray blank preparation and preconditioning of test materials were kept constant to ensure reliable results. The test materials were identical, with the exception of the substrate thickness, which varied in a constant scale. The analysis of forming quality was done by evaluating the structure of the creases after forming. Samples of tray corners were embedded in acryl plastic to preserve the shape of the creases during processing. Then, the samples were ground, polished, and analysed with an optical microscope. The creases were analysed in the machine direction, cross direction, and at a 45 degree angle. The samples were then measured and compared to each other to determine if the material thickness had an effect on the crease geometry and the quality of the tray rim.

3.4 Process monitoring

The performance of a substrate in the forming process is generally evaluated by observing the end product as in this case, a ready-made paperboard tray. In Paper III, a destructive testing (DT) method for material performance was presented. A method for monitoring dimensional accuracy was discussed in Paper VI and a real time monitoring method for forming forces was introduced in Paper VII.

3.4.1 Convertibility evaluation of press formed materials

The performance of biopolymer dispersion coated paperboards was tested with a series of converting tests (Paper III). The testing methods were selected from practical solutions used in the converting industry to achieve realistic results in the material performance in package production. Paperboard tray manufacturing was chosen as the testing process due to the versatility and challenge of the included converting methods.

Press forming tools were designed and manufactured to create an informative testing setup. First, the shape and dimensions of the tray were selected and then the rest of the testing tray was drawn according to common design principles of the packaging industry. The test tray used in the converting trials was designed to be demanding to form in order to obtain differing results between the studied materials. The combination of a fairly large (38 mm) tray height and a steep angle of the tray wall (12˚) made the forming process difficult to control successfully. The length of the tray is 265 mm and the width is 162 mm. In addition, the creasing pattern of the blank was designed to represent a typical pattern used by the packaging industry.

The main parameters of the press forming process were varied, and the produced paperboard trays were observed. The effect of the female mould temperature, the blank holding force of the rim tool and the pressing speed on the end product quality was analysed. The heat tolerance of the test substrates was evaluated by discovering the mould temperature where the sticking of the polymer coating onto the tool surfaces started. Press forming causes defects mainly in the corners of produced trays when the material properties of the paperboard are insufficient to endure the forming forces. The rupturing of tray corners at different process parameter values was evaluated on the basis of the number of ruptures and by measuring the length of the ruptures. These parameters were selected to evaluation because they are clearly measurable and easy to interpret.

3.4.2 Tray dimension measurement

Dimensional accuracy of trays made of polymer-coated paperboard and the effect of all essential press forming process parameters on the outer dimensions of the trays was studied (Paper VI). The data was obtained for press forming and lid sealing process optimization and forming tool design. The paperboard trays were analysed and measured with a quality monitoring system that includes a smart camera and a backlit table. Trays with varying dimensions were heat-sealed using an industrial scale sealing machine to investigate the effect of the package size and the product weight to the residual oxygen in the headspace gas of the package. Three different set of weights were used to simulate packed products; 25 g for light products such as snacks, 200 g and 400 g for other, heavier food stuff.

The adjustment of outer dimensions in the press forming of paperboard trays is a more complex task compared to thermoformed plastic packages which are cut to the desired outer dimensions after the forming phase. In press forming of paperboard trays, the length and the width of the tray can be altered by changing the blank size or by adjusting the forming process parameters. The trays for the dimensional measurement were press formed by varying all the essential process parameters: blank holding force, pressing force, female mould temperature, dwell time, and pressing speed.

Gastronorm (GN) sizes are standard sizes of containers used in the catering industry, specified in the EN 631 standards (SFS-EN 2006). The mould set used in the tray production was designed according to the GN1/4-standard size: 265 x 162 x 38 mm and deviation of outer dimensions from target values was observed.

Ready-made paperboard trays were analysed with a quality monitoring system which is part of the LUT Packaging Line. The system transfers inverted trays with a manipulator on a backlit table after the press forming phase. The background light brings out defects of the trays and enables accurate measuring of dimensions. Each tray was photographed with a Cognex IS5605-11 smart camera 20 seconds after press forming. In that period of time, the trays cooled down to the room temperature and settled in the final outer dimensions. The images were taken 650 mm above the tray bottom to prevent image distortion. The smart camera takes black and white images with a resolution of 2456 x 2048. The vision software recognizes patterns and calculates the dimensions of the measured object automatically. The trays were measured also under a compression load caused by a 4 kg weight placed on the bottom of the inverted tray. An example of an image processed by the monitoring system can be seen in Figure 12.

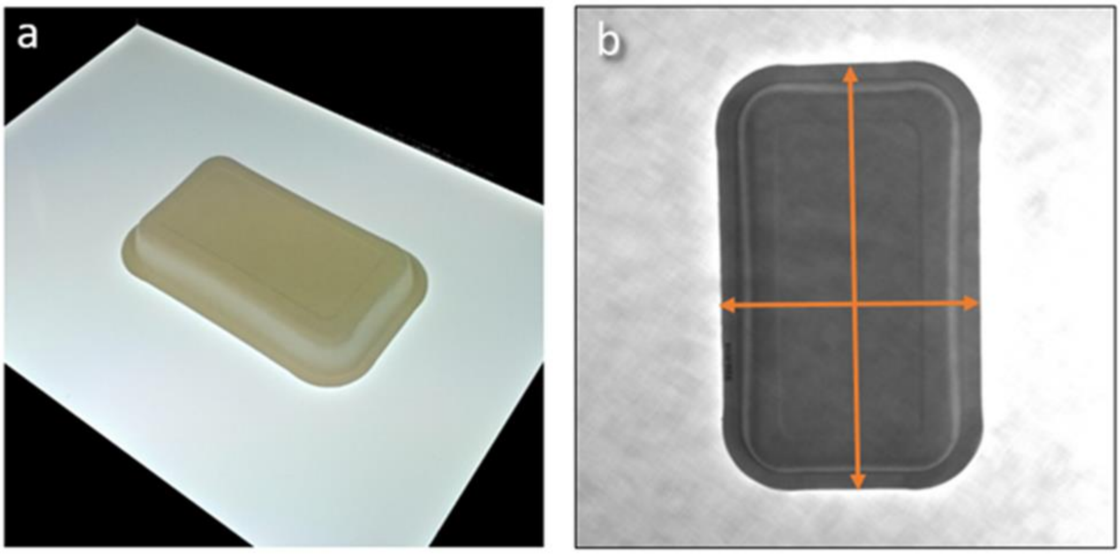

Figure 12: (a) Test tray on the backlit table of the quality monitoring system, (b) Image of the test tray taken with the smart camera and outer dimensions measured with pattern recognition.

3.4.3 Forming force measurement

The material properties of the formed substrate, e.g. paperboard, are measured in laboratory conditions comprehensively, but the properties are likely to change during the forming process. For example, rapid heat transmission from the forming tools can cause local and gradual softening in the substrate. It also releases water vapour from within the fibre structure, which has an effect on the behaviour of the substrate.

A novel monitoring setup of forming force was developed to obtain real-time data of paperboard tray production and more thorough understanding of phenomena related to the tool-substrate interaction in press forming and tray forming (Paper VII).

The new monitoring setup utilizes the construction of the existing production grade press forming mould that produces rectangular trays with the size of 215 x 127 x 45 mm. The female mould and the rim tool remained unmodified, but a new male mould was designed and manufactured. The original male mould of the tool set was a one-piece one, and the fastening configuration was machined on the reverse side of the moulding surface. The new male mould includes two parts – a mould part with embedded force sensors and a fastening part. Accurate monitoring of the forming process requires the use of multiple force sensors that allow more detailed measurement data to be obtained, and therefore four miniature column load cells (nonlinearity ±1%, hysteresis ±1%) were placed into cavities that were precision-machined in the corners of the male mould, which can be seen in Figure 13. The depth of the cavities is dimensioned so that when the maximum force limit of the sensor (13 kN) is reached, the sensor is compressed and the mould part and the fastening part are in contact with each other. This prevents damage to the sensors and misinterpretation of the measured values is unlikely since the maximum can be detected as the flat region of the force curve. The mould part is attached to the fastening part with a floating fixing that allows an angular change of 0.7 degrees. This enables the forming force to be distributed on each force sensor in relation to the formation of the converted substrate.

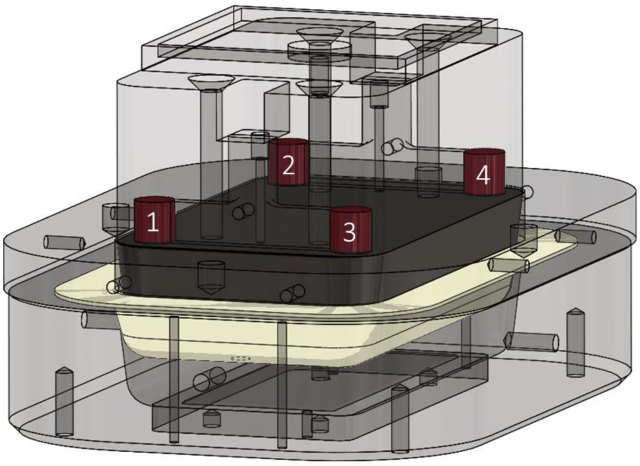

Figure 13: Press forming tool set and location of the force sensors 1-4 in precision-machined cavities in the corners of the male mould.

The monitoring setup produces forming force - mould position curves out of data obtained from the force sensors and a position sensor, which are connected to the control logic software of the LUT Packaging Line. The sensors are connected to the Beckhoff-logic using 1-channel input terminals and a separate power supply.

The pressing force, Fp, applied by the male mould to the substrate can be measured by installing force sensors in the tool set. In addition, the magnitude of the blank holding force, F_{BH}, can generally be adjusted/measured in press forming machines as it is one of the main process parameters. By knowing these two values, the friction force and coefficient of friction between the tool surface and the substrate can be calculated. The forces directed to the formed substrate can be seen in Figure 14.

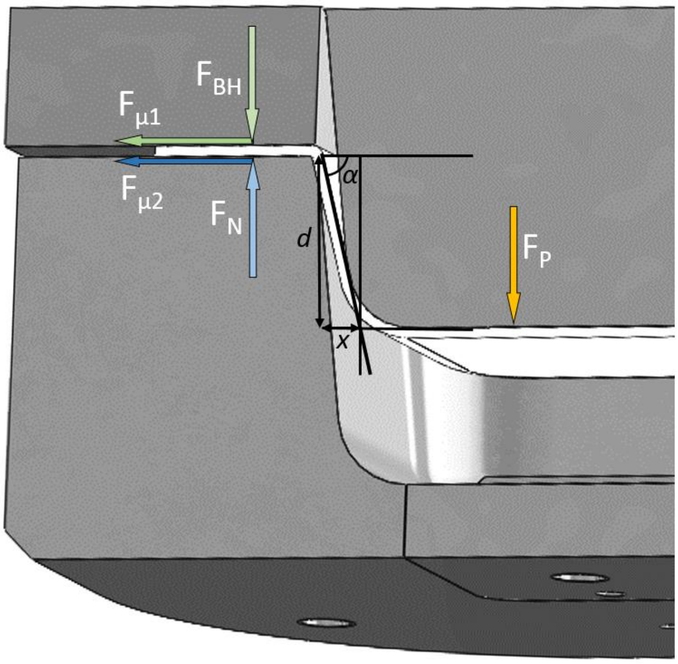

Figure 14: Essential forces in the press forming process during the forming phase, where α denotes the angle of substrate transfer, d denotes forming depth, x denotes the distance between the folding edges, F_P denotes the pressing force, F_{BH} denotes the blank holding force, and F_N denotes the normal force to the blank holding force. $F_{\mu 1}$ and $F_{\mu 2}$ denote the corresponding friction forces.

The relationship between the pressing force and the blank holding force can be established by dividing the pressing force to components. The pressing force can be divided to force components by using the trigonometric function presented in Figure 15.

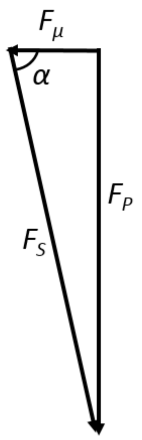

Figure 15: Force components of pressing force, where Fs denotes the force transferred by the substrate.

The angle of substrate transfer and the friction force can be calculated using the equations:

$$tan \propto \ = \frac{d}{x} \quad (2)$$

$$F_\mu = \frac{F_P}{tan\propto} = \frac{F_P x}{d} \quad (3)$$

The friction force can also be divided into the following components:

$$F_\mu = F_{\mu 1} + F_{\mu 2} = F_{BH}\mu_1 + F_N\mu_2 = F_{BH}(\mu_1 + \mu_2) \quad (4)$$

The sum of the coefficients of friction can be derived from equations 3 and 4:

$$\mu_1 + \mu_2 = \frac{F_P x}{F_{BH} d} \quad (5)$$

These formulae can be used to evaluate the pressing force and to determine the part of the force required to counter the blank-holding force and the part that is due to other forming phenomena. The force values obtained with the monitoring setup were used in the calculation of kinetic friction coefficients for each material. The friction coefficients of the test materials were measured by two different methods. Force values obtained with the monitoring setup were used in the calculation of coefficients, and the materials were also tested with a standardized laboratory method. The effect of heat on the forming force and the correlation between laboratory measurements and data obtained with the monitoring setup was analysed. The monitoring setup was also utilized to detect rupturing, which can occur during the forming phase of paperboard trays.

The coefficient of friction values between the substrate and the metal surface were measured according to the applied standard ASTM D 1894-63. In this measuring method, a specimen (64 x 140 mm) was attached to a sled which was pulled across a machined steel surface at the speed of 200 mm/minute. Friction forces were measured with the force sensors and kinetic friction values were calculated by using the monitoring setup. The measurement method differed from normal press forming in the way that instead of using a pre-creased tool-shaped tray blank, a smooth rectangular sample (140 x 300 mm) was positioned between the female mould and the rim tool. Other differences were substantially higher pressing speed (12000 mm/minute) and sliding of the substrate conforming the tool geometry. The pressing speed could be adjusted to equivalent speed in comparison to the laboratory test method, but measurement performed with the typical production speed is more advantageous. As a consequence, the measured values represent kinetic friction during press forming production runs. The following illustration (Figure 16) demonstrates the forming of the test specimen.

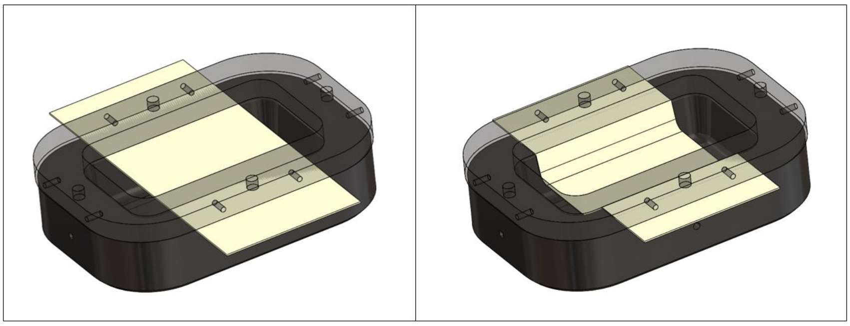

Figure 16: Test specimen before and after friction measurement. The specimen sheet is positioned between the female mould and the rim tool (transparent in the illustration). The male mould is not visible in the illustration.

4. Results and Discussion

4.1 Tray blank preparation

Factors affecting the die cutting tool and creasing pattern design were studied in Papers IV and V.

4.1.1 Die cutting tool

The convertibility of different biopolymer dispersion coated and PE-coated paperboards was studied by using creasing tools with various geometries (Paper IV).

The pressing force of the die cutting tool was adjusted with preliminary tests. Initially the blanks were produced from PE- and PET-coated samples with the force of 170 N / cm of crease. However, this force, when applied onto biopolymer-coated samples, resulted in visible cracking of the coating surface. The pressing force had to be reduced by 30% to 120 N / cm to obtain the required quality of creases. The creases had no visible damages in the coating layer, and the shape of the crease was considered suitable for the press forming stage. The pressing force remained constant in all converting tests.

A complex state of forces is exerted on paperboard during die-cutting (cutting and creasing). Such as tensile, compressional and shear forces occur in the creasing zone due to bending and pressing of the board into the groove beneath the rule. This set of stresses, operating over a very small area, can cause cracks in the coating, thus resulting in decreased barrier properties of the product (Andersson 2008).

The coefficient of friction was used to estimate the ratio of the force of friction between the tip of the creasing rule and the surface of the coating layer. The magnitude of forces transmitting into the coating surface correlates with the friction properties of the test materials. Starch-based coatings had the smallest coefficients of friction, and therefore the die cutting process is less intense for them.

Although the quality of the creases was as desired in the initial observations, converting the samples with a 120 N / cm pressing force resulted in micro-cracking of the starch-based dual-polymer coatings. Although the die cutting process was less intense for the starch-based samples, the more brittle structure (Kuusipalo 2001; Rättö et al. 2012) of the coating layer was the likely cause of micro-cracking. However, these cracks were not visible with the naked eye, but detectable with a scanning electron microscope (SEM). In addition, with toolsets 1-5, the amount of cracks in the barrier layers was less frequent in SEM-imaging than with the worn toolset 6.

The pressing force used in the die cutting of the sample materials had to be decreased by 30% to preserve the integrity of the coating layer for the biocoated materials. Nevertheless, the used force resulted in micro-cracking of the starch-based dual-polymer coatings and in the creation of a small amount of pinholes in all biopolymer coatings. An additional reduction to the pressing force could preserve the integrity of the barrier coating layer fully. However, in such a case the functionality of the tray blank could be compromised due to insufficient formation of creases.

The effects of the tool geometry were observed by analysing the ready-made trays. With selected tray pressing process parameters, the differences in the formation of the trays between samples die-cut with different tool sets could not be clearly observed visually without magnification. The tray corners folded similarly and the quality of the tray flange remained uniform with all samples. The appearance of the creases could be characterized as slightly better in trays pressed from blanks with narrower creases (toolsets 1, 2 and 3).

The geometry of the creases was evaluated from microscopic images. Visual differences between creases produced with different toolsets were minimal in the blank stage due to spring back in the paperboard surface. In the tray stage, the dimensions of the folded creases varied 5-10% with different toolsets. The measured variation in folded crease dimensions in the tray stage with one tool set and one material was below 2%. The toolsets with wider creasing grooves (4, 5 and 6) produced wider folds with smaller thicknesses into the tray walls. Differences in coating materials did not have any notable effect on the dimensions of the folded creases. Examples of creases after press forming are presented in Figure 17.

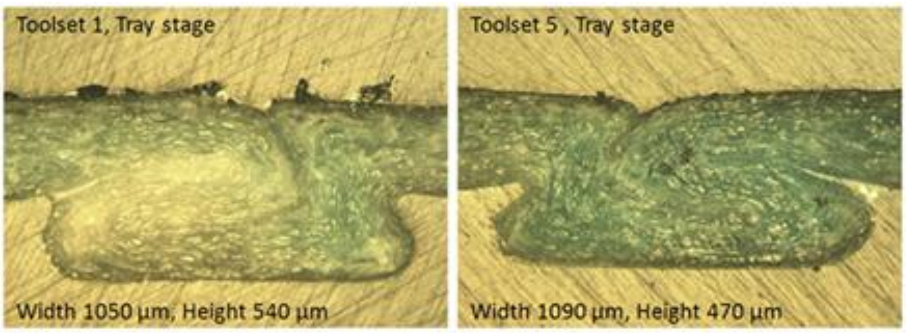

Figure 17: Microscopic cross-section images of creases diecut with toolsets 1 and 5 into material with starch-based coating. The most significant dimensional difference is in the height of the crease.

The integrity of barrier coating in tray blanks and in ready-made trays was analysed with pinhole detection. The extrusion PE-coated reference material 4 was not damaged by any of the tool sets (see Figure 18), which was partly expected due to the plasticization of the coating layer and a slightly higher strength upon stress of the material compared to materials with starch-based coating (1-2) and the material with polyolefin coating (3).

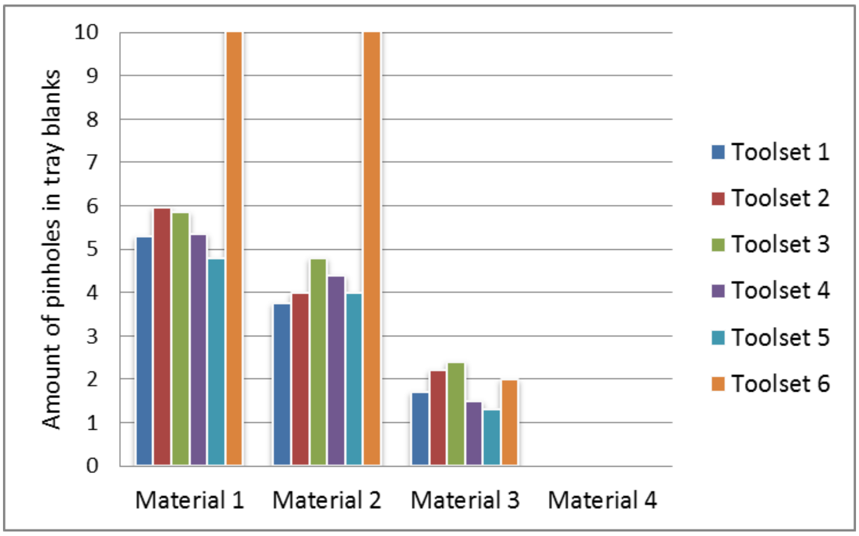

Figure 18: Number of observed pinholes in tray blanks.

The effect of tool geometry had only a minor impact on pinhole creation, except in the case of the worn toolset 6 which caused substantial damage to the coating layers of materials 1 and 2 (in Paper IV). Effect of the worn toolset was likely to be caused by infiltration of the dispersion polymers into the base substrate and the creation of a brittle surface when using starch-based barrier chemicals. Compressive forces inserted on the die-cut side dominate in the die-cutting process, and Kuusipalo (2001) has shown that the convertibility of the material, especially with starch-based extrusion coatings, is hindered when exposed to compression forces. A similar trend was observed here with starch-based dispersion barrier coatings.

Pinholes were also inspected for in the ready-made paperboard trays. The folding of the blank hindered the inspection of pinholes in tray corners; hence pinholes may be located on top of each other in different layers. When inspecting trays pressed from the materials that had a large number of pinholes (materials 1 and 2) in the blank stage, the visible number of pinholes was smaller in the ready-made trays. This implies that some of the existing pinholes in the die area were not accessible for the colouring solution due to the folding of the paperboard. The number of pinholes was about 15% higher in the ready-made tray stage with material 3 compared to the blank stage, and it can be presumed that the difference was not greater with samples 1 and 2. The PE-coated samples did not have pinholes in the ready-made tray stage, either. The results obtained from the ready-made trays therefore correlated with the blank tray stage results.

The pursuit of reducing the stresses and thus the amount of pinholes in the coating layer by widening the creasing grooves had only a minor influence. The narrower grooves performed similarly as the wider ones, and by using them, the space between the adjacent creases can be altered more freely, making them preferable. With all materials, straight creasing grooves performed slightly better compared to conical ones. A conical shape in the groove walls increased the number of pinholes slightly in spite of the smoothened shape of the creases. The conical shape leaves a tighter clearance for paperboard in the bottom of the groove and thus facilitates the creation of pinholes.

In Paper V, the effect of the creasing rule width was studied by producing rectangular trays (265 x 162 x 38 mm) that were press formed using a similar creasing pattern with all crease widths. The value of 1.4 for the creasing coefficient that was found in Paper IV to optimize the behaviour of the creases was used with all tool sets. The process parameters were kept constant in the press forming phase of the die-cut blanks. The tray wall area was visually estimated to be smoother, with narrower creases, but a more noticeable difference was found in the tray flange, an area on which lidding film sealing is performed. The folding in some of the creases was uneven and one-sided, which would make successful lid-sealing impossible.

The number of creases on one tray of unacceptable quality, resulting from different crease widths, is presented in Figure 19.

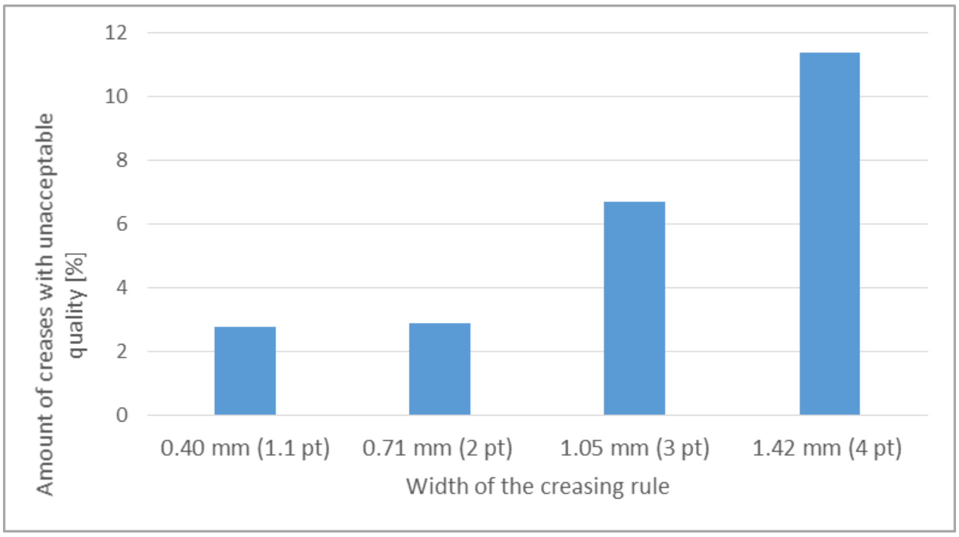

Figure 19: The number of creases with unacceptable quality resulting from different creasing rule widths. The values are the average of ten trays.

The creases die-cut with rule widths of 0.40 and 0.71 mm folded most desirably, and the use of wider rules produced a substantially greater number of unacceptable creases. However, the die cutting tool with the thinnest rule width (0.40 mm) caused some problems during die cutting, and the pressing force had to be very carefully adjusted to prevent cracking of the polymer coating layer. Even slightly too large force caused the creasing rule to cut through the polymer coating layer. The tools with wider creasing rules did not cause the same outcomes. Based on the results, 0.71 mm wide creasing rules were evaluated to perform in the most desirable manner in blank preparation.

4.1.2 Blank design

The effect of the creasing pattern on the quality of crease formation was evaluated by observing the quality of folding and the flatness of the tray flange. Unacceptable creases were not formed properly, and the corresponding folds had large gaps in the tray flange area, which would make tight lidding of the tray impossible. A pair of unacceptable creases is marked in Figure 20.

Figure 20: Unacceptable creases in the tray flange. The creases have not been formed adequately, leaving a gap between the flat areas surrounding the crease.

The number of creases with acceptable and unacceptable quality in a single tray resulting from different creasing patterns is shown in Figure 21.

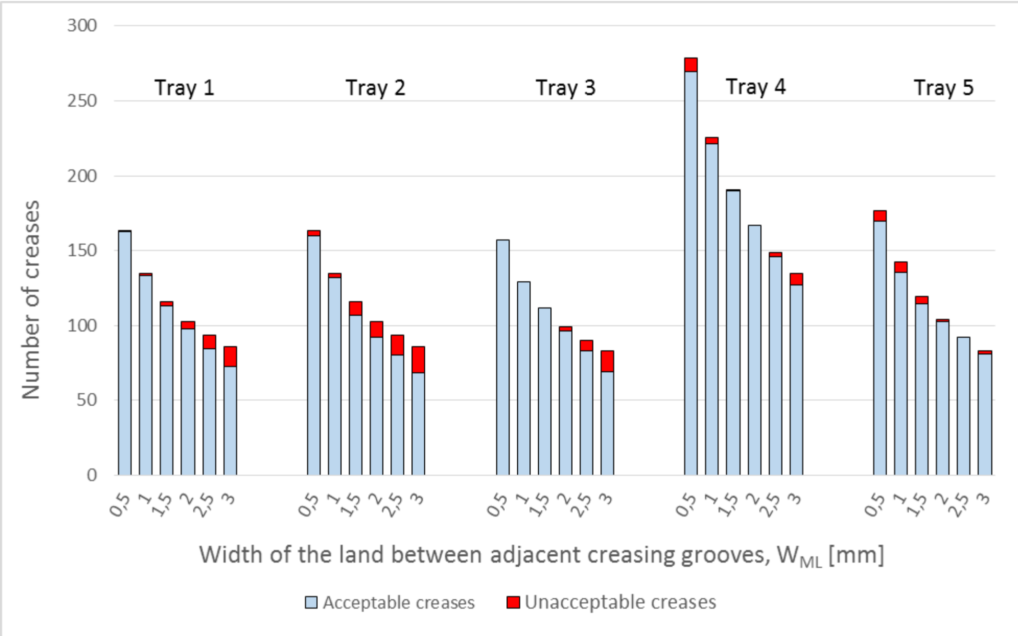

Figure 21: Functionality of the creases in test trays.

In trays with the smallest blank corner radius, r_{BC} (trays 1, 2, and 3), a greater distance between adjacent creases correlated with an increased number of unacceptable creases.

The substrate folded more evenly and the wall of the tray was smoother when the material had more possibilities (folds) to compact during the press forming phase. However, when the land between the adjacent creasing grooves was 0.5 mm, the durability of the thin land in the matrix was a cause for concern, especially when a plastic matrix was used. Therefore, the minimum width of the land between the creasing grooves should be limited to 1.0 mm. In trays 1, 2, and 3, the number of creases was as high as possible in the tray corner within the limitations of the creasing rule and groove dimensions discussed above. Tray 2 could not be produced without unacceptable creases, which indicates that the clearance between the male and female mould was not correct everywhere and the mould set needed modification. Trays 4 and 5, which had larger blank corner radii, were more successful when a greater distance between adjacent creases was used. The smoothness of the tray walls was considered best when the greatest number of creases was used for all the trays. However, the quality of the tray flange has to be prioritized to ensure package tightness. The following formulas were established on the basis of the trial runs.

The minimum distance (C_{dmin}) between adjacent creases (from the centre line of one rule to another) was defined as

$$C_{dmin} = W_{CG} + W_{ML} \tag{6}$$

where W_{CG} is the creasing groove width and W_{ML} is the width of the land between adjacent creasing grooves. W_{ML} is 1 mm when the radius of the blank corner is below 80 mm. W_{ML} is 2 mm when the radius of the blank corner is 80 to 110 mm. Further testing with different mould sets should be performed to make the recommended values more accurate. Also testing of other types of paperboard in further studies is advisable.

The quantity of creases in the first set (90° tray corner) was defined as

$$Q_{c1} = \frac{(2\pi \cdot r_1)/4}{C_{d\,\min}} = \frac{\pi \cdot r_1}{2C_{d\,\min}} \tag{7}$$

Sets of shorter creases should be placed regularly between longer creases.

The angle between adjacent creases in the first set was defined as

$$A_{c1} = \frac{90°}{Q_{c1}} \tag{8}$$

Finally, the radius of the second crease set is

$$r_2 = 2r_1 \tag{9}$$

Additional creases should be placed on each side of the corner creases to avoid wrinkles (folds that are not assisted by creases) in the walls of the tray. These creases are placed perpendicular to the sides of the blank and are full-length. The distance between the creases can be calculated with Eq. 6. The number of additional creases was optimized to 3 to 4 for the tested tray designs, depending on the tray shape.

4.1.3 Summary

The results of the study show that it is possible to produce press formed paperboard trays that fulfil all the required functional and visual properties when the creasing pattern and die cutting tools are designed as a combination by following the presented principles.

Tray blank production is less sensitive to the adjustment of the die cutting force compared to the production of creases used in folding. The force could be reduced significantly to preserve the integrity of the polymer coating layer. The folding of the blank would cause irregular creases, but in press forming the blank operated as desired. Possibility to reduce die cutting force is useful when more delicate materials are die cut and press formed. The condition of the creasing matrix was emphasized when more delicate samples were die cut.

In tool design, the instructions provided by creasing tool manufacturers are a suitable baseline for the die cutting paperboard tray blanks. The wider creases, die cut with the wider rules, cannot be utilized to compact more material in tray corners. Creases die cut with narrower rule widths folded the most desirably, and the use of wider rules produced a substantially greater number of unacceptable creases. The geometry of the creasing grooves had a minor influence on the dimensions of the creases, but the narrower creasing grooves would allow more flexibility in the design of the creasing pattern. The origin of pinholes existing in the ready-made trays is primarily in the die-cutting process, provided that the converted material is immaculate before processing, which underlines the importance of the die cutting phase.

In creasing pattern design, the number of creases in the tray corner is the most important variable when the trays are produced by press forming. The substrate folds more evenly and the wall of the tray is smoother when the material has a greater number of folds to compact during the press forming process. The creases positioned radially toward the rotation axis of the tray corner assist the folding of the paperboard blank most suitably, and the correct number of creases can be determined on the basis of the radius of the blank corner.

The hypothesis related to the blank preparation was found correct although the geometry of the die cutting tools had lower effect than it was expected on the crease formation in press forming.

In further studies, the equations used in the creasing pattern design should be developed to be more accurate by testing different mould sets and substrates.

4.2 Press forming tool development

The development of the press forming tool was discussed in Papers I and II. The effect of tool heating arrangement was studied in Paper I and the effect of the mould clearance in Paper II.

4.2.1 Heating arrangement of the press forming tool

The novel forming tool design (Figure 22), including the geometry of the oil chamber and layout of the heating element tubes, seeks to achieve optimum temperature performance for the best end product quality.

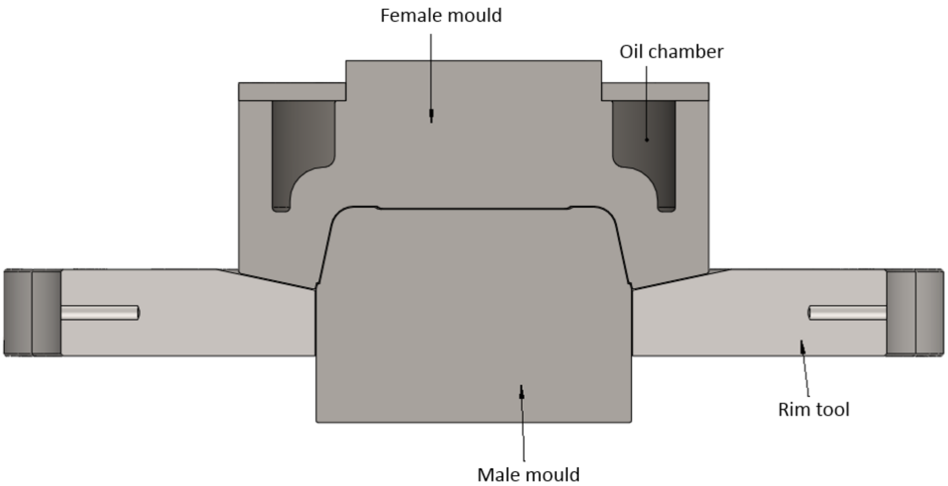

Figure 22: Novel oil-filled mould design.

The mould developed is structurally less complex and, as a result, easier to fabricate than moulds with multiple heating elements. Adding an oil chamber to the mould tool is accomplished simply by milling a hollow cavity into the backside. The shape of the oil chamber prevents leakages because the oil level is below the sealing faces of the mould. Also the ventilating system and wide sealing faces secure the tightness of the oil chamber. The machining process is simple, because the geometry tolerance and surface finish requirements for the chamber can be flexible, and the milling can be done from one direction and in one setup.

Thermographic images of the new female mould design taken at production temperature showed uniform heat distribution in the mould parts that are in contact with the tray blank, see Figure 23. The thermal load transferred to the paperboard blank is expected to be uniform as well.

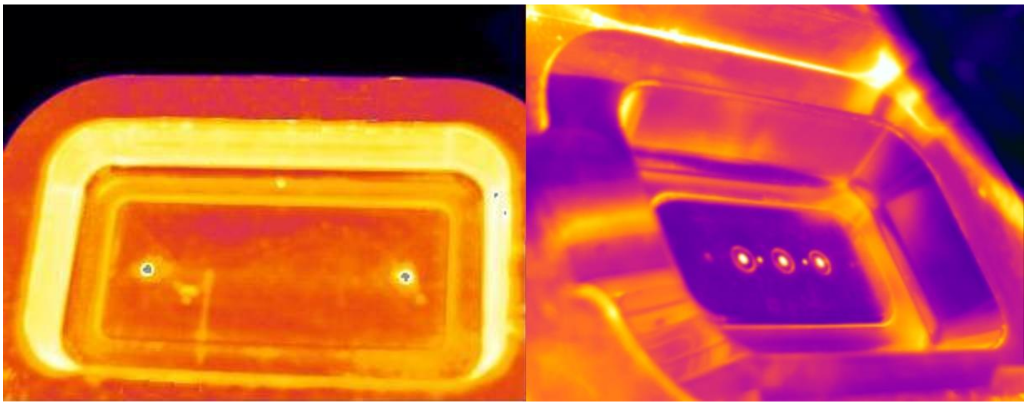

Figure 23: New mould with even heat distribution on the left, traditional mould showing irregular heat distribution on the right.

The great heat capacity of the oil (2580 J/(kg*K)) in the mould makes it possible to control the overall mould temperature change better throughout a production run. To verify the functional production performance of the new design, the same short production runs of 35 trays were performed with the new mould as well. The temperature drop observed from the beginning to the end of the run was 11°C. This is a 39% improvement over the drop seen with traditional mould tooling.

Sealing the oil reservoir of the mould is crucial because paperboard trays are used mainly in the packaging of food products. Food legislation sets strict standards for the package manufacturing industry, and compliance with these standards is the overriding basis for mould design and manufacturing. The structure of the oil chamber lid is presented in Figure 24.

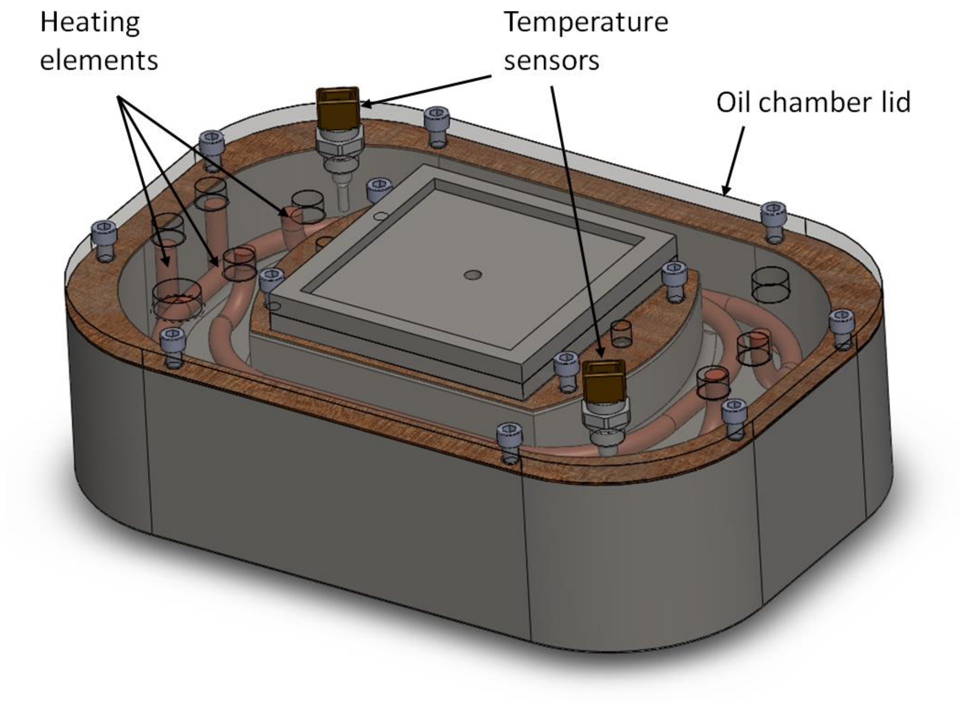

Figure 24: Heating elements and the oil chamber lid of the new mould. The forming surface of the mould tool is heated by the hot oil that fills a large cavity in the tool. Shaped from bendable tube elements and immersed in the oil reservoir, three electric heaters establish and maintain the temperature.

The sealing of the oil reservoir, the associated lead-throughs, and the ventilating system were considered in the design phase of the new mould setup, acknowledging resulting negative effects on the rigidity of the mould structure. The ultimate shape of the oil chamber was influenced by these strength demands and practical needs. The mould tool had to be strong enough to withstand the large press forces of tray forming, and it must include structural features that allow secure attachment to the press. The new mould is a careful compromise seeking to optimize heat performance. The fastening features of the mould tool were located where they would have a minimal effect on tray quality, *i.e.*, in the middle of the mould tool flat corresponding to the bottom flat of the paperboard tray.

In the developed mould, the heating elements can be controlled individually according to temperature data obtained from several temperature sensors. Efficient heat transfer oil ensures that the heating element heat input is distributed evenly to the forming surfaces of the tools. The material thickness between the oil chamber and the moulding surfaces is kept constant to enable easier control of heat flow through the metal wall. These features of the mould tool design ensure optimum temperature control, and consequently more precise control of the forming process.

4.2.2 Mould clearance of the press forming tool

The effect of paperboard thickness and mould clearance on the final product of the press forming process was studied in Paper II. The usages of mould clearance and tray wall quality evaluations at observation points A to J are presented in Table 4.

Table 4: Folding and compaction of paperboard in tray pressing.

Observation points	Distance from the tray bottom [mm]	Length of compressed paperboard blank compared to original length in one corner	190 + PET 40		230 + PET 40		310 + PET 40		350 + PET 40	
			Usage of mould clearance	Tray wall quality	Usage of mould clearance	Tray wall quality	Usage of mould clearance	Tray wall quality	Usage of mould clearance	Tray wall quality
A	0	84.70 %	49.81 %	**-2**	57.19 %	**-2**	80.24 %	**-1**	85.78 %	**-1**
B	5	84.58 %	49.88 %	**-2**	57.27 %	**-2**	80.36 %	**-1**	85.90 %	**-1**
C	10	75.46 %	55.91 %	**-2**	64.19 %	**-2**	90.07 %	**-1**	96.28 %	**0**
D	15	67.63 %	62.38 %	**-2**	71.63 %	**-1**	100.51 %	**0**	107.44 %	**0**
E	20	61.76 %	68.31 %	**-2**	78.43 %	**-1**	110.06 %	**0**	117.65 %	**0**
F	25	58.15 %	72.55 %	**-1**	83.29 %	**-1**	116.88 %	**0**	124.94 %	**0**
G	30	53.55 %	78.79 %	**-1**	90.46 %	**-1**	126.93 %	**0**	135.69 %	**+1**
H	35	51.49 %	81.94 %	**-1**	94.08 %	**-1**	132.01 %	**0**	141.11 %	**+1**
I	38	50.23 %	83.99 %	**-1**	96.43 %	**0**	135.31 %	**1**	144.65 %	**+1**
J	38	57.37 %	73.53 %	**0**	84.43 %	**0**	118.47 %	**0**	126.64 %	**0**

Based on these results, the usage of mould clearance should be from 95% to 135% for the tested paperboard types when forming the selected example trays. This result cannot be applied to other paperboard types without further tests. The relation of material thickness to forming mould clearance depends on the strength properties, density and z-directional compressibility of the formed materials and the surface friction between the blank and the moulds. Mould clearance between male and female moulds does not affect the tray flange area (observation point J). The tray flange is flattened between the rim tool and female mould, and the flattening force can be adjusted independently; therefore, all materials have grade 0 at observation point J. As expected, the formation of creases was similar in each corner of the tray.

Observation points B, D, G, and I were selected for microscopic analysis. Because the process parameters used in this study were constant for each material, elongation was largest with the material of the smallest grammage (190 + 40). The shape of the creases therefore varied more, and the width of the crease was larger. The shape of the creases between 230+40 and 190+40 was quite similar, but elongation was significantly higher with the thinner material. The higher strength properties of the thicker materials, such as 310 + 40 and 350 + 40, decreased the variations in crease shape. The width of the crease was more compact. Dimensional measurements of creases were made with all material thicknesses. Two adjacent creases were measured from each sample. The averages of these measurements are presented in Table 5.

Table 5: Crease length averages.

Grammage [gsm]	Material thickness before forming [µm]	Crease width average [µm]
190+40	270	1003
230+40	310	901
310+40	435	856
350+40	465	809

The formation of creases varied less and the shape of the creases was more homogenous with 350 + 40, which had the best usage of mould clearance. With every material thickness, there was some variance in crease formation. However, a conclusion can be made regarding the width of press formed creases, which decreased when the material thickness increased. In press forming, creases in each tested material seemed to perform on average similarly in the cross direction, machine direction, and at a 45 degree angle. With lower material thicknesses, such as 190 + 40 and 230 + 40, the paperboard also became wrinkled in areas that were not creased, which had an effect on the overall visual quality of the package. This could have been caused by too large mould clearance or the lower in-plane stiffness of the thinner materials.

4.2.3 Summary

Many factors can be altered during the production of press formed paperboard trays, like process parameters, the moisture content of the substrate and the material to be converted, but the mould heating arrangement and the mould clearance can be considered constant factors. The hypothesis related to the mould features was confirmed to be correct and the mould heating arrangement and the mould clearance had a significant effect on the tray quality.

Even though most of the forming moulds are in an even temperature before the production run, irregular heat distribution and drop of the surface temperature are in most cases common during production. A new, improved mould heating arrangement was developed in order to achieve uniform temperature distribution. The new heating arrangement simplifies mould tool fabrication and eliminates the need for several machining set-ups. The added feature promising the biggest improvement is the heating system that uses oil to distribute heat evenly. The tray forming surface temperature is more uniform in the newly developed oil-heated mould tooling than that observed in typical traditional tray moulds. The new design provides about a 39% improvement in temperature drop compared to the traditional mould tooling.

In the mould design phase, the mould clearance is determined by the thickness of the formed substrate. Mould clearance usage needs to be sufficient to ensure the correct formation of creases and smoothening of the tray corner surface. Overuse of mould clearance causes fracturing and visual defects on the paperboard surface. The usage of mould clearance should be from 95% to 135% for the paperboard types used in the tests. The result indicate that too great clearance is more likely to cause problems in the press forming process, and therefore the clearance should be specified to be narrow in relation to the material thickness. The evaluation of microscope images revealed that the width of the press formed creases decreases when the material thickness increases. On average, in press forming the creases in each tested material seemed to perform similarly in the cross direction, machine direction, and at a 45 degree angle. Consequently, mould clearance could be specified constant around the tray corner area.

In further studies, different types of substrates should be tested in order to understand better the effect of material properties on a suitable usage of mould clearance.

4.3 Process monitoring

In Paper III, a destructive testing (DT) method for material performance was presented. A method for monitoring dimensional accuracy was discussed in Paper VI and a real time monitoring method for forming forces was introduced in Paper VII.

4.3.1 Convertibility evaluation of press formed materials

The performance of the biopolymer dispersion coated paperboards in press forming was tested with a series of converting tests in Paper III. The effect of the female mould temperature, the blank holding force and the pressing speed on the end product quality were analysed.

Preliminary tests were used to determine the process parameters for the forming tests, and it was quickly discovered that the heat tolerance of the coating was a limiting material property. The dispersion barrier coating started to stick onto the surface of the rim tool (the dispersion barrier -coated side of paperboard, the pigment-coated side facing the hot female mould) already at 80 ˚C in the case of certain material samples, revealing that both the starch-based dispersion coating and the starch-synthetic dispersion coating had an affinity to tackiness at higher temperatures. The sticking of the coating to the mould, causing rupturing in the trays, was thus a limiting factor with regard to convertibility. The female mould temperature used in the forming tests, in which the blank holding force and the pressing speed were changed, had to be reduced to 100 ˚C. However, a mould temperature of 160 ˚C would be preferable for this baseboard on the basis of earlier experiences.

It was presumed that a rise in the female mould temperature would improve the formability of these materials, which was also confirmed with testing. The rupturing of paperboard decreased with nearly all samples when the mould temperature increased. Even though paperboard did not rupture in any of the 22˚C tests, formability was insufficient in all of them due to lack of formability of the base paperboard at low temperatures. The tendency of barrier coating for sticking at higher temperatures limited the usable mould temperatures, and the best formability was observed for samples that endured a 140˚C mould temperature.

The strength properties of the materials were evaluated on basis of the effect of blank holding force on material rupturing. It was discovered that differences in the dispersion coating layer did not have a significant effect on the rupturing tendency of the tray corners. The formability and strength of the base paperboard, which was the same in all materials, determined the results in this case.

Unlike other tests, the pressing speed test did not produce clear results, and conclusions regarding the effect of pressing speed could not be made.

4.3.2 Tray dimension measurement

After the ready-made tray is released from the forming unit, a varying amount of spring back occurs during the cool down, and the outer dimensions of the tray increase. Residual stress within the substrate causes spring back when the tray is no longer clamped between the moulds. The effect of all essential press forming process parameters on the tray dimensions was studied with a series of tests (Paper VI). Each process parameter was changed separately and other parameters were kept constant in the following set values: male mould temperature 50 ºC, female mould temperature 160 ºC, blank holding force 1.6 kN, pressing force 120 kN, dwell time 600 ms, and pressing speed 150 mm/s.

All the presented values were the average of five measured sample trays. The variance of the measured dimension values was at the same level for all tests in which only one process parameter was changed (standard deviation 0.25-0.35 mm). The mould length and width of the tray, which are marked in figures 25 and 26 represent the dimensions that the tray had when the forming moulds were pressed against each other.

Even though the blank holding force was found to be one of the most important process parameters in press forming in the other Papers, it had no substantial effect on the outer dimensions of the tray. The pressing force also had only a minor effect on the tray dimensions. Most of the force is applicable only in the flange flattening stage, and the amount of the force causing the folding and sliding of the blank can be expected to be invariant.

In contrast to the blank holding force and the pressing force, the temperature of the female mould had a significant effect on the tray dimensions, as presented in Figure 25. The length of the tray was reduced by 8.0 mm and the width by 10.7 mm when the mould was heated from 22 ˚C to 180 ˚C. Mould temperatures above 180 ˚C caused bubbling of the polymer coating layer and sticking between the coating layer and the steel surface of the mould. The tray quality was sufficient in the mould temperature range from 140 ˚C to 180 ˚C where the length of the tray changed by 3.4 mm and the width by 6.8 mm. The dimensional change was significantly greater in the cross direction (CD) than in the machine direction (MD).

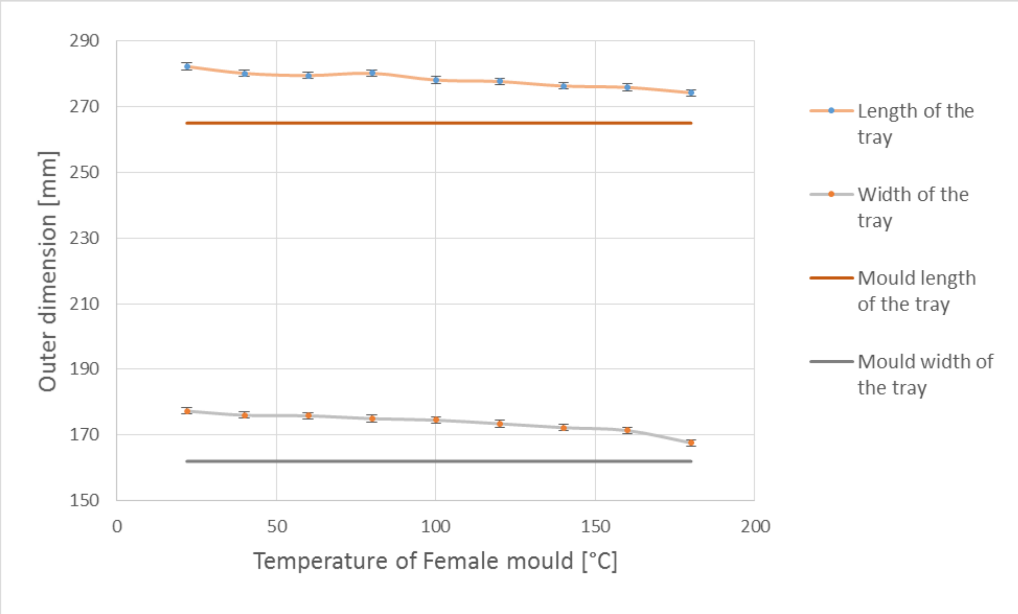

Figure 25: The effect of female mould temperature on the outer dimensions of the tray.

The amount of heat conducted to the tray depends on the dwell time along with the mould temperatures. Increase of the dwell time has an effect on the temperature reached in the bulk of the complex, making it higher. This affects also the water evaporation. The use of longer dwell time results in smaller trays. A dwell time longer than 600 ms caused bubbling of the polymer coating layer at the mould temperature of 180 ˚C. The whole dwell time range could be used with the female mould temperature of 160 ˚C. The length of the tray was reduced by 7.7 mm and the width by 11.4 mm when the dwell time was extended from 0 ms to 2000 ms, as presented in Figure 26.

The main disadvantage of a longer dwell time is the reduction of production speed. When the dwell time was increased from 400 ms to 1000 ms, the production speed decreased from 31 trays/min to 24 trays/min.

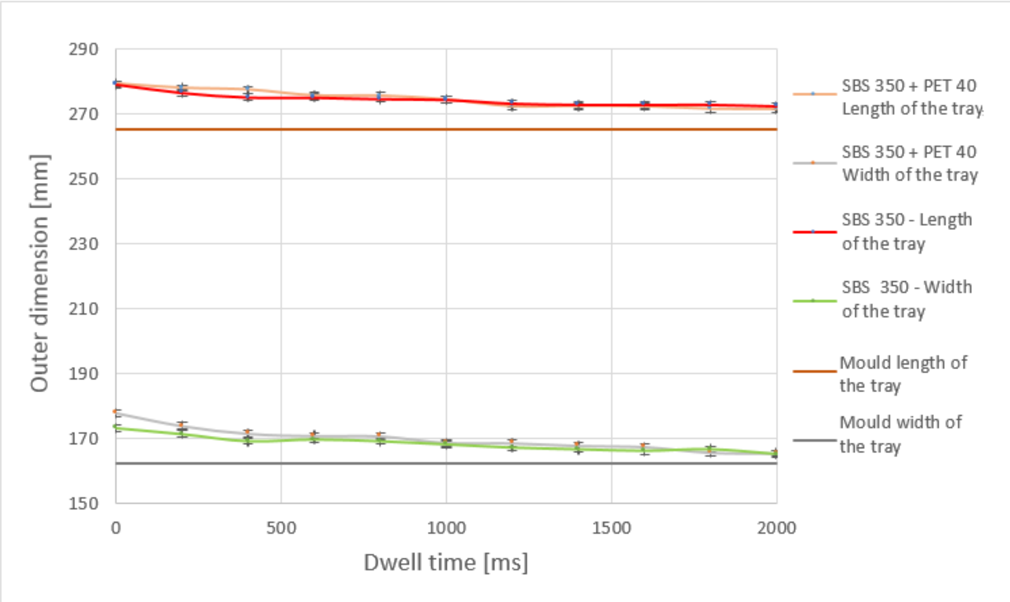

Figure 26: The effect of dwell time on the tray dimensions with the female mould temperature of 160 ˚C.

Test substrate SBS 350 was tested also without the polymer coating. From the dimensional point of view, the substrate performed similarly with and without the PET-coating, and consequently the spring back phenomenon can be attributed to the material properties of the baseboard.

Increasing the pressing speed caused an increase to the tray dimensions. This can be explained with the amount of heat transmitted to the formed substrate. With greater speeds, the blank spends a shorter period of time in contact with the heated mould. An advantage of greater pressing speed is the increase of production speed, but this advantage may be lost if the dimensions of the tray have to be altered with a longer dwell time.

The moisture content of the substrate was 9.1% in the blank stage. The change in moisture content was measured from ready-made trays produced by using different dwell times (female mould temperature 160 ºC, blank holding force 1.6 kN and pressing speed 150 mm/s). The moisture content was reduced by 1.45 percentage points during the press forming process from polymer-coated SBS 350 + 40 PET. The same base substrate without the polymer coating dried up by 2.7 percentage points, which was due to the fact that moisture could evaporate from both sides of the material. The greater drying of the uncoated base board compared to the PET-coated one did not have an effect on the amount of spring back, which can be seen in Figure 26.

Dimensional change describes how much the outer dimensions of the tray increase when 4 kg weight compresses the tray (Figure 27). The amount of dimensional change indicates that the rigidity of the ready-made tray vary as a function of the dwell time. The tested trays were expected to be more rigid in the MD, which was confirmed by the fact that the length of the tray did not change substantially when a dwell time over 200 ms was used. In the CD (width of the tray), the effect of compression load reduced almost linearly when the dwell time was increased. The improvement of the tray rigidity slowed down when the dwell time was prolonged over 500 ms, which therefore can be recommended as the lower limit for the dwell time at the female mould temperature of 160 ºC.

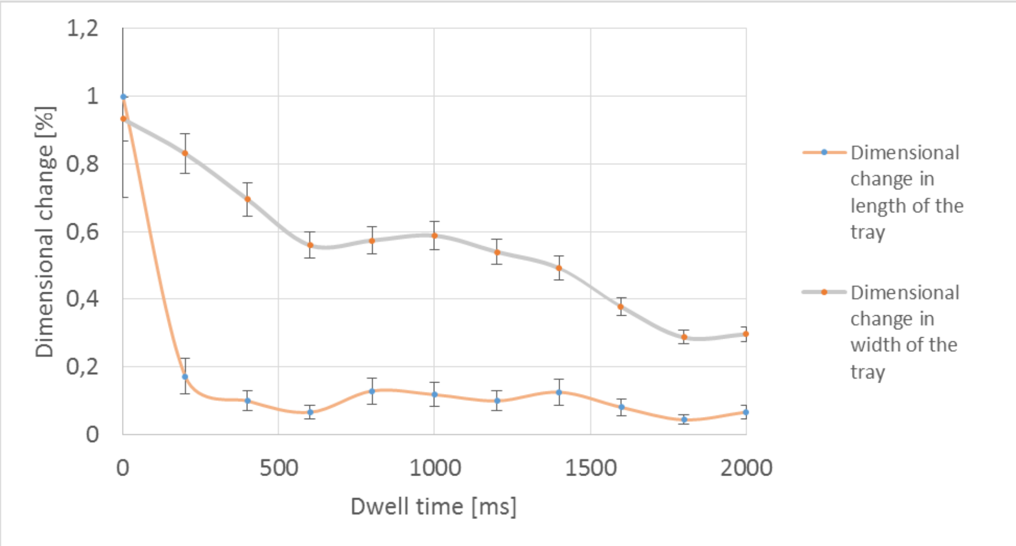

Figure 27: The effect of dwell time on dimensional changes in a tray under load.

All the measured trays were bigger both in length and in width compared to the design values of the mould set. The difference between the design values of dimensions and the tray dimensions was most likely material-dependent and further studies with different materials are needed.

The effect of tray dimensions on the lid sealing process was studied by heat-sealing filled trays. The lid-sealing process reduced the size of the trays and evened out the size differences substantially. The sealing tools force the dimensions of the tray to reduce and the sealed lidding film prevents spring back. The greatest difference in the outer dimensions of the trays was 8 mm (length) – 10 mm (width) before sealing, and only 4.8

– 6.3 mm afterwards. The size changes were the smallest in the more compact trays with the largest product mass.

In Paper VI, only the outer dimensions of the trays were measured, but the monitoring system is suitable for more versatile analysis. Pattern recognition can be used to detect ruptures, fractures and wrinkles in the paperboard surface. Wrinkles and the smallest ruptures require a light source on the foreground to enable detection. In industrial press forming this is a poorly applicable method, as the exterior of the tray has usually multicolour print, and complex printing makes pattern recognition extremely demanding. That is why the detection methods should utilize mainly background lightning. Bigger fractures can be detected in visible light through the opening and smaller fractures in the tray walls in the contour shape of the tray.

4.3.3 Forming force measurement

The performance of the novel monitoring system was validated with a series of tests in Paper VII. Figure 28 shows an example of the recorded pressing force as a function of the pressing depth determined with 4 pressure sensors. The curves describe the behaviour of the substrate under stresses throughout the press forming process.

The curves for the individual force sensors are identical, confirming that the pressing force is evenly distributed on the blank and that the different parts of the mould set are accurately aligned. The total pressing force, which is the sum of the forces recorded by the individual sensors, shows a gradual increase at first, after which the force remains relatively stable between depth of 15 and 37 mm. At the end of the press forming phase (depths 37–45 mm), where crease-assisted folds in the tray walls are flattened, a greater variation can be observed between the individual curves. This indicates that the timing of the forming is slightly different in each corner due to the operation of creases.

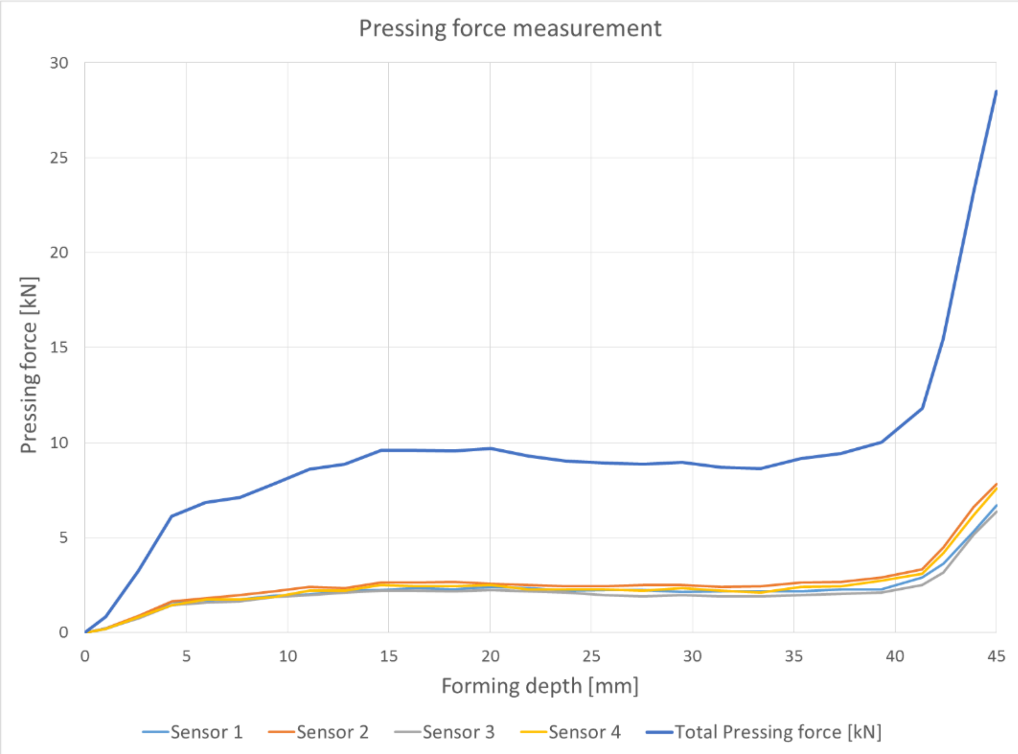

Figure 28: Force curves obtained from sensors 1–4 and the curve of the total pressing force (sum of sensor values) plotted against the forming depth. The curves represent the formation of a tray with good quality.

The monitoring system was also utilized in the detection of defects during the press forming process. Rupturing of the formed substrate is one of the common defects emerging in press forming of a paperboard substrate. This can be caused by insufficient strength properties of the substrate in relation to the tool geometry or the process parameters (typically excessive blank holding force). Also sticking of the polymer coating to the tool surface can cause ruptures when too high mould temperatures are used. A rupture can be detected from a significant change in the shape of the force curve, which can be seen in Figure 29.

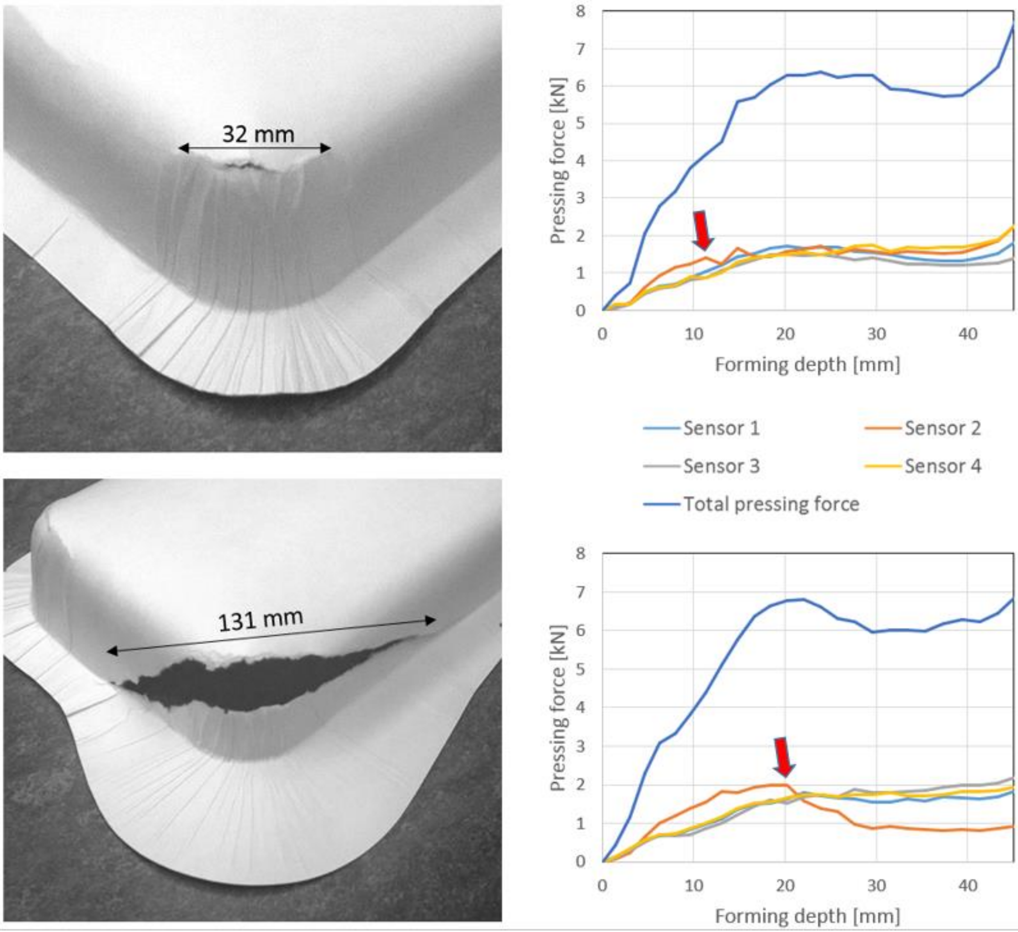

Figure 29: Graphs obtained from individual force sensors. The uniformity of force curves describe the performance of the press forming process. A sudden drop in the force curve indicates rupturing (marked with a red arrow) of the substrate. Above: a smaller fracture (length 32 mm) detected by sensor 2 using 1.7 kN blank holding force. Below: a very large rupture (length 131 mm) detected by sensor 2 using 2.5 kN blank holding force.

In analogic processes, the forming force is typically measured only with a single sensor. The results obtained with this measurement method correspond to the total pressing force presented in Figure 28. The use of multiple force sensors makes it possible to obtain more detailed information about changes in the pressing force during the forming phase. The location of the rupture in the tray is indicated by the individual sensor, and the forming depth of which the rupture occurs can be observed from the position of the drop in the force curve on the x-axis. The magnitude of the rupture can be estimated from the shape of the force curve. A continuing drop in the force curve indicates that rupturing of the substrate continues.

The force values obtained with the monitoring setup (forming depths 5-30 mm, blank holding force 1.8 kN) were used in the calculation of kinetic friction coefficients for each material. The calculation was conducted with Equations 2-4. The materials were tested with the moulds at 23˚C and in the case of heated moulds at 140˚C (female mould) and 60˚C (male mould). The specimens were cut so that the longer edge was parallel to MD or CD depending on the test. The results of the laboratory friction test and those obtained with the new device are shown in Figure 30.

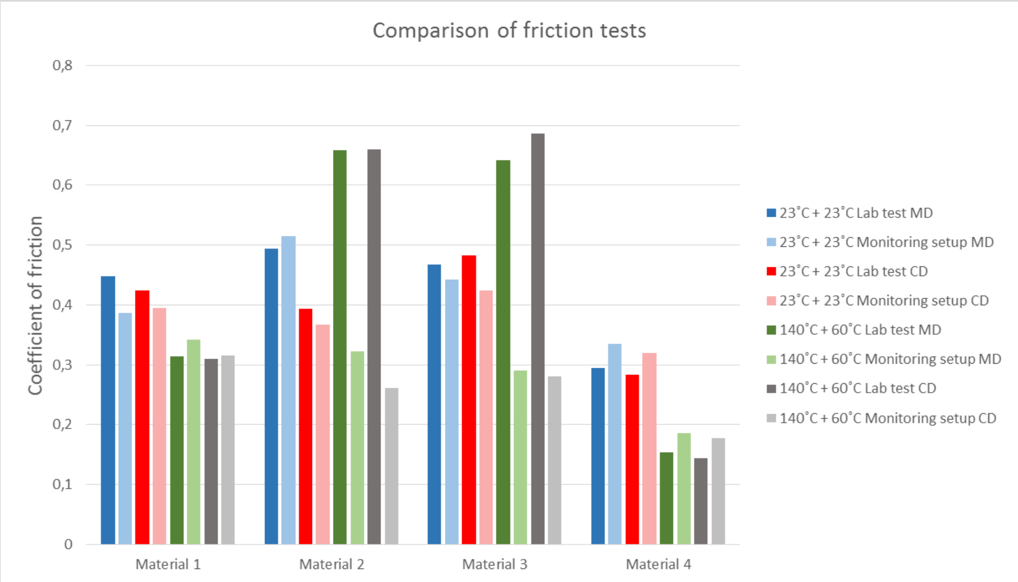

Figure 30: The results of kinetic friction tests obtained from the standard laboratory tests and the monitoring setup. The values are presented as a sum of friction coefficients from both sides of the substrate.

Both measurement methods gave fairly similar results when the measurements were performed with the moulds at 23˚C. The results prove that the novel method can be used in the estimation of friction at a reasonable level. This enables evaluation of friction by using only inbuilt components within the production machinery. Materials 1 and 4 performed as expected on the basis of the laboratory measurements: addition of heat decreased the coefficient of friction. Laboratory measurements with materials 2 and 3 indicated that the coefficient value would increase significantly, whereas the effect of heat was observed to be the opposite. This was probably due to the longer dwell time in the laboratory measurement compared to the pressing process and the heat-sensitiveness of polyethylene films, whose melting temperature has been reported to be below 120°C, which is considerably less than that of PET (Duraccio et al. 2015; El-Saftawya et al.

2014). During the converting tests, slight accumulation of moisture originated from the paperboard and a waxy substance, probably PE, onto the female mould took place at the higher mould temperature. The presence of moisture on the tools is thus a probable explanation why the friction values of materials 2 and 3 differed from the other studied samples in the press forming. This observation emphasizes the importance of cleaning the tools when friction measurements of heat-sensitive materials are carried out to correspond with laboratory measurement, but it should be noted that moisture and the other mentioned factors are present in production-scale press forming. That is why friction measurements performed with tools in production condition have significant benefits.

The monitoring setup provides a total value which is a sum of the coefficient of frictions on the both sides of the substrate. The coefficient values are different in the polymer-coated side and the board side of the substrate. If test material is available without polymer coating and both sides of the substrate are similar, testing of the substrate provides coefficient value for the base board. These results make it possible to determine the coefficient value for the side that is being altered, e.g. polymer-coated, printed, or varnished. It is thus possible to utilize the results of a laboratory analysis to determine the coefficient for any side of the substrate.

The monitoring system was used for the evaluation of material heat behaviour in press forming. Changing the mould temperature has an effect on the formability of the substrate. The elongation at break of the substrate increases due to greater plastic deformation (Back and Salmen 1989). Raising the mould temperature increases the amount of heat conducted to the substrate and typically improves the formability of paperboard materials. This phenomenon can be seen in Figure 31, where elevation of the mould temperature led to a decrease in pressing force.

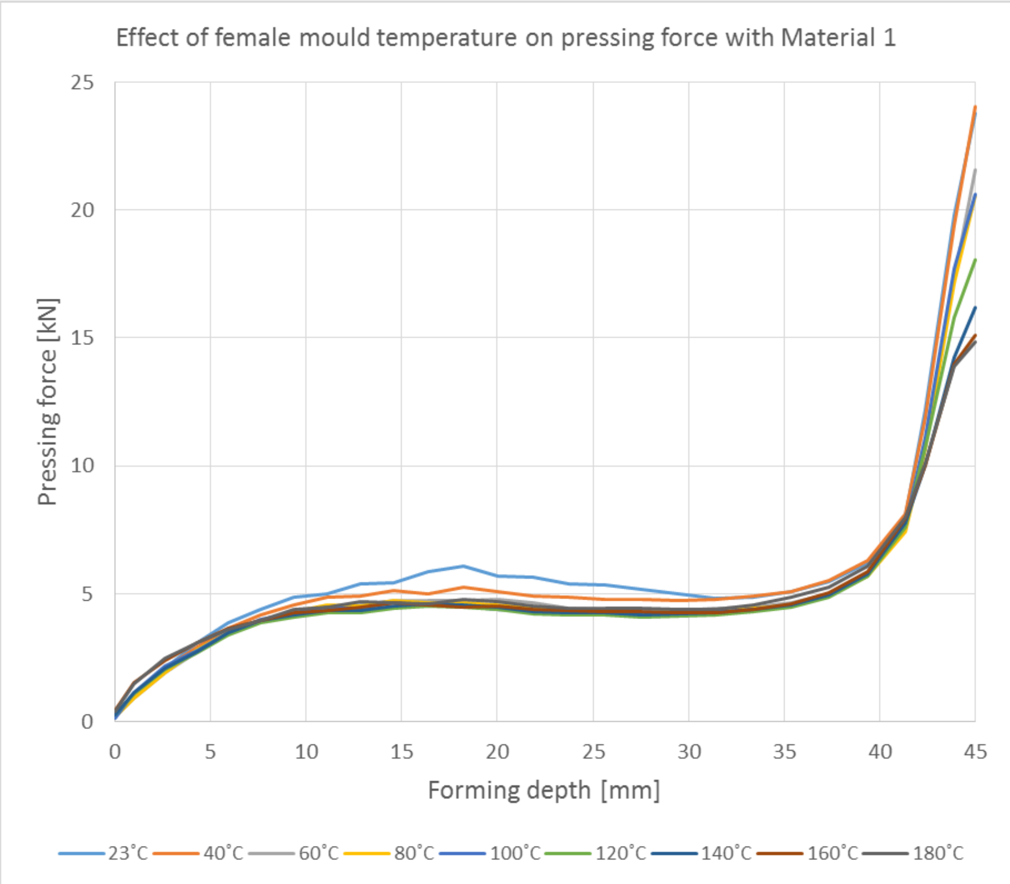

Figure 31: Pressing force applied to Material 1 with different female mould temperatures. The pressing force in the end of the forming stroke decreased by 38 per cent when the temperature of the female mould was raised from 23 to 180 ˚C (blank holding force 1.0 kN).

The measured pressing force decreased by approximately 20 per cent when the temperature of the female mould was raised from 23 to 80°C. Higher mould temperatures had no significant effect on the force values up to forming depths of 0–42 mm, but at the end of the press forming phase (depths of 42–45 mm), where crease-assisted folds in the tray walls are flattened, the effect of mould temperature was evident; the higher the mould temperature the lower the pressing force.

Material behaviour differences in press forming were also evaluated by using the monitoring system. The materials were tested with two sets of process parameters to study the effect of mould temperatures on the pressing force. A change in the magnitude of the pressing force was observed with all tested substrates, see Figure 32. Part of the change was due to a reduction in the friction, but the remaining part was probably related to an improved formability.

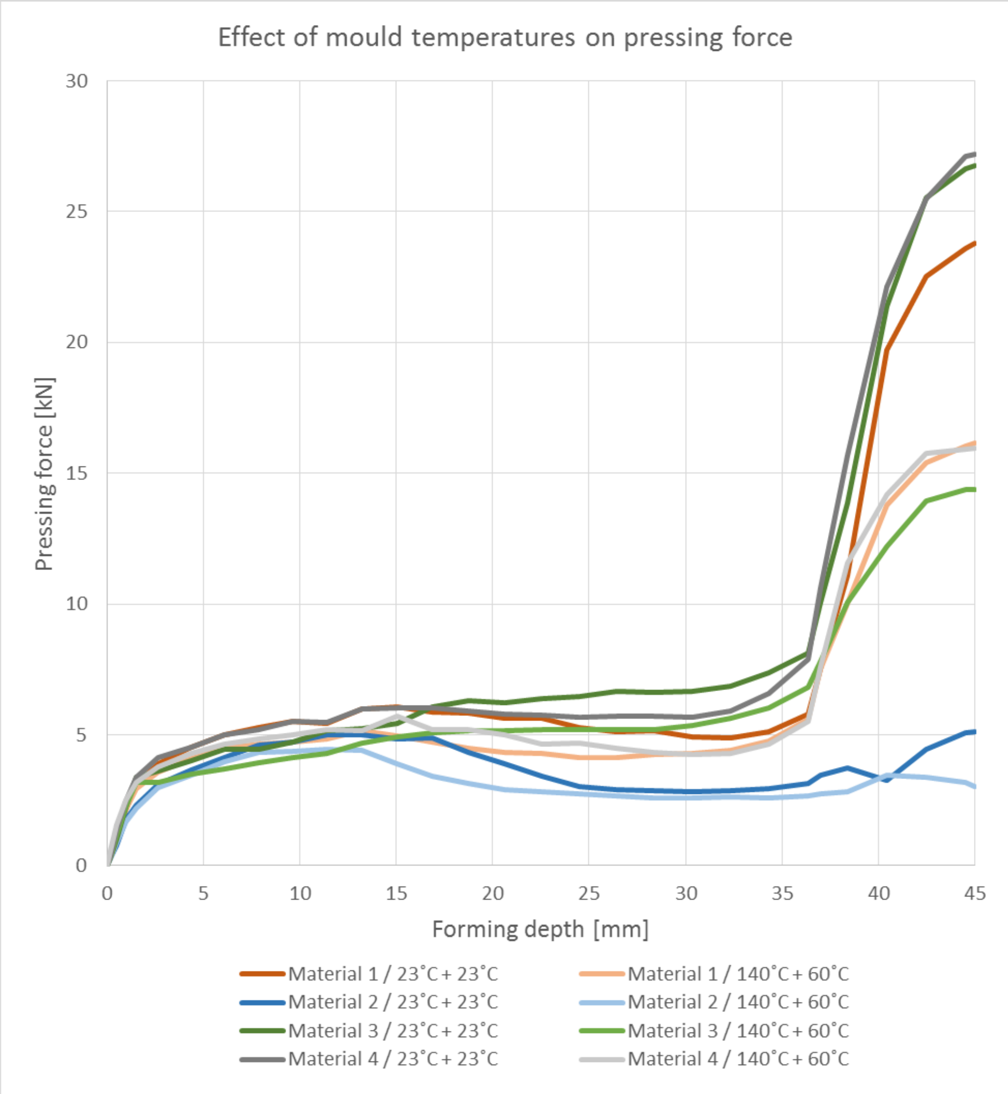

Figure 32: Effect of mould temperatures on pressing force. The tests performed with moulds at a standard laboratory temperature and with heated moulds (female mould temperature 140°C and male mould temperature 60°C). The blank holding force was adjusted to 1.0 kN in all cases.

The pressing force was reduced by 32 % with material 1 and by 41–46 % with materials 2–4 when the mould temperatures were raised. Other materials were press formed into trays with acceptable quality but material 2 did not withstand the stresses and ruptured severely, presumably because of its low tensile strength.

4.3.4 Summary

The convertibility tests performed in Paper III represent an informative test series that can be carried out on a production machine. The method does not necessarily require any additional measuring devices, which would naturally facilitate and speed up the testing. The heat tolerance of the materials can be studied by changing the mould temperatures, the strength properties of the materials by changing the blank holding force, etc. The size and number of ruptures in tray corners show how the tested material responds to change in the process parameters. When different substrates are evaluated, *e.g.* in production start-up, the blank holding force which starts rupturing of the material and/or length of ruptures describe the formability of materials indicatively when otherwise constant process parameters are used.

All heat-related parameters, *i.e.* mould temperatures, dwell time, and pressing speed, can be used to adjust the outer dimensions of the paperboard tray. The only process parameter that does not have an effect on the production speed is the temperature of the female mould, making it the primary parameter in the dimension adjustment. The required amount of heat should be pursued by using as high a mould temperature as possible. The upper limit of the usable mould temperature is usually limited by bubbling or melting of the polymer coating layer. When the mould temperature is set high, the rest of the required amount of heat can be achieved by adjusting the dwell time correctly and optimizing the production speed simultaneously. The functionality of the mould heating arrangement is crucial to the dimensional accuracy of the trays, the temperature drop of 18˚C during production run observed in Paper I equalled a dimensional change of over 2% in the outer dimensions of the tray. The resulting tray quality obtained with the new mould heating arrangement is improved as there is less variance in the outer dimensions of the trays. The effect of pressing speed on the tray dimensions is relatively small compared to the effect on production speed, and therefore it should not be used in dimensional adjustment.

The produced trays with dimensions closest to the mould length and width caused no problems in the sealing machine either in the package transfer or in the lid sealing phases. With alteration of the blank size, sealed trays can be modified exactly to GN-standard dimensions. However, the functionality of trays in the lid sealing process or in transport box packaging does not require it. Most likely, the first defect caused by a small oversize is a visual one – the printing in the tray lid may not fit into the shape of the tray.

All produced trays were measured to be bigger both in length and in width compared to the design values of the mould set. This means that the mould set has to be designed to be undersized to obtain trays with certain outer dimensions. The length of the tray mould should be 4% and the width 5.5% smaller than the desired trays with the tested tray design and substrate combination. Using this dimensioning, the process window of press forming allows for fine tuning of dimensions during the production without compromising the other properties of the trays and production speed reduction.

A novel measuring method and the developed device enable monitoring of the press forming process in real time and also makes analysis of certain material properties (surface friction, heat induced effects) possible when using production machinery. An existing mould set was successfully modified for force measurement by replacing the male mould with a new one that included a set of sensors. The detection of defects requires the use of multiple force sensors that allow more detailed measurement data to be obtained. The location of the rupture in the tray, forming depth in which the rupture occurs and the indicative size of the rupture can be determined on the basis of individual sensor detection and by evaluating the shape of the force-position curves.

The effect of mould temperature on the pressing force was observed to be consistent for all the tested materials. The pressing force decreased by 32-46% in the end part of the press forming phase, where the crease-assisted folds in the tray walls are flattened, when the temperature of the female mould was raised from 23 to 140 ˚C. Respectively, the coefficient of friction between the mould surface and the tested materials was reduced by 12-44%. Part of the reduction of the pressing force was therefore due to reduction of friction, but the remaining part can be considered to be related to the enhanced formability of the test substrates.

The coefficient of kinetic friction values obtained with the standardized laboratory test method and the new monitoring setup were fairly similar when the measurements were performed with the moulds at 23˚C. When heated mould set (140˚C female mould and 60˚C male mould) was used in press forming, the laboratory measurements with PE-coated materials indicated that the coefficient value would increase significantly compared to the colder mould values. The effect of heat was observed to be the opposite, which was believed to be due to accumulation of moisture originated from the paperboard on the mould surfaces. The results showed that actual friction between the mould surface and the formed substrate during the forming process can differ significantly from the expectations made on the basis of laboratory tests. This observation emphasizes the benefits that can be achieved by a measurement method that utilizes a production-scale forming tool set.

Further studies are needed to find out how the amount of undersizing in the mould design phase can be estimated. The difference between the design values of the dimensions and the tray dimensions depends on the material properties of the formed substrate, and further studies with different materials are needed. The hypothesis related to the process control was verified to be correct and therefore development of the process control system that utilizes a combination of dimensional measurement and pressing force monitoring should be included in further studies.

5. Conclusions

The first objective of the thesis was to develop advanced converting tools for production-scale press forming of paperboard trays. The operation of the die cutting and press forming tools was evaluated and principles for tool design were introduced.

The **creasing pattern** and the **die cutting tools** should be designed as a combination on the basis of the thickness of the formed substrate. The origin of pinholes existing in the coating layer of ready-made trays is primarily in the die-cutting process, which emphasizes the importance of the die cutting phase. Tray blank production is less sensitive for the adjustment of **die cutting force** compared to the production of the creases used in folding. The force can be reduced significantly to preserve the integrity of the polymer coating layer without compromising the operation of creases during the folding of the tray corner. The use of narrower creases is recommendable as it does not have an adverse effect on the formation of creases and it allows more flexibility in the design of the creasing pattern. The number of creases in the tray corner is the most important variable in pattern design. The correct number of creases can be determined on the basis of the radius of the blank corner, and the creases should be positioned radially toward the rotation axis of the tray corner. An optimized creasing pattern produces evenly folded and smoother tray corners.

Evaluation of the current press forming tools revealed that irregular heat distribution and drop of the surface temperature are common phenomena during production runs. The improved **mould heating arrangement** enables more uniform surface temperature and thereby stabilizes the press forming process. The **mould clearance** can be determined by the thickness of the formed substrate. Mould clearance usage needs to be sufficient to ensure correct formation of creases and smoothening of the tray corner surface. The results of the study indicate that the clearance should be specified to be narrow in relation to the material thickness, in other words, the usage of mould clearance should be over 100% around the tray walls.

The second objective was to develop monitoring methods that enable the production of paperboard trays with enhanced quality and can be utilized in process control.

A destructive testing method for material analysis is applicable for tests performed solely on production machinery. When a **monitoring setup** based on pattern recognition is incorporated into the control system, the outer **dimensions** of the produced trays can be managed by using feedback. All heat-related parameters can be used to adjust the outer dimensions of the paperboard trays. The temperature of the female mould can be considered as the primary parameter in dimension adjustment. The production speed can be optimized when the temperature of the female mould is set to the usable maximum and the rest of the required amount of heat is achieved by adjusting the dwell time. From the process control point view, the mould set is preferable to be designed as undersized to obtain trays with certain outer dimensions due to the spring back of the tray walls. Further studies are required for the estimation of the end product dimensions in the mould design phase.

The press forming process can be **monitored** in real-time by using a set of **force sensors** that are embedded into the male mould. The method can be utilized in the evaluation of material characteristics, e.g. formability, coefficient of friction, temperature response and defect sensitivity, by using production machinery. Especially friction between the mould surface and the formed substrate during the forming process can differ significantly from the expectations made on the basis of laboratory tests.

In conclusion, it is possible to produce press formed paperboard trays that fulfil all the required functional and visual properties when the converting tools are optimized and substrate to be converted has sufficient material properties. The combination of dimensional measurement and pressing force monitoring enable the creation of adaptive process control that includes the detection of defects and tracking of changes in the material properties.

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