The Durability of Press-formed Paperboard Trays – Effects of Sealing and Drying

Arvo Niini,* Ville Leminen, Panu Tanninen, Juha Varis, and Teija Laukala

Dimensional measurements were recorded to observe the durability of press-formed paperboard trays used for food processing *via* heating and cooling of the paperboard trays containing oatmeal. A set of the studied press-formed paperboard trays were dried before being heated, and a set of the paperboard trays were heat-sealed before being cooled to compare the effects of drying and sealing on the durability of the tray. In addition, empty trays were heated to observe the impact of food processing conditions on its durability *via* leak tests with a colouring solution as well as optical analysis of the material coating on the surface of the trays. The drying process of the trays was observed to improve the dimensional stability of the trays while being heated, and heat-sealing the trays yielded a major positive impact on the dimensional stability of the trays while being cooled. The leak tests and optical analysis results on the heated empty trays showed a negative durability impact from the food processing conditions. It was concluded that adjusting the heat-sealing parameters and food processing conditions is necessary in order to achieve improved durability of the press-formed paperboard trays for food processing purposes.

Keywords: Dimensional stability; Heat-sealing; Curling; Creep; Crystallization

*Contact information: Lappeenranta-Lahti University of Technology LUT, Mechanical Engineering, Yliopistonkatu 34, Lappeenranta 53850 Finland; *Corresponding author: Arvo.Niini@lut.fi*

INTRODUCTION

Paperboard trays manufactured *via* press-forming are used as food containers for many types of foodstuffs. The environmental conditions during the processing of foodstuffs affect the mechanical and material properties of these paperboard trays. Sustained durability in food processing is essential to achieve a desirable performance from press-formed paperboard trays in terms of food packaging solutions.

In previous studies, the effects of the press-forming parameters and humidity conditions on the durability of press-formed paperboard trays used in food processing showed material curling and stiffness degradation as the primary negative outcomes (Niini *et al*. 2020a,b). A lower moisture content in paperboard trays, achieved by drying the trays before food processing, was shown to improve the tray durability, as moisture absorption during the food processing was connected to the emergence of hygroscopic strains in the paperboard fibres due to hygroexpansion (Niini *et al*. 2020b).

Moisture content greatly affects the mechanical properties of paperboard materials, with an increased moisture content leading to a linearly decreasing tensile strength, tensile stiffness, and bending stiffness, both in the fibre machine direction (MD) and the fibre cross direction (CD) of the paperboard materials (Marin *et al*. 2020a). On top of weakened material tensile properties, in terms of the mechanical performance of paperboard, increased moisture absorption was found to result in severely degraded compression strength of the paperboard (Marin *et al*. 2020b).

The impact of sealing in terms of the mitigation of stiffness degradation and material curling in press-formed paperboard trays used in food processing has not been studied before. A common method for sealing press-formed paperboard trays is heat-sealing, in which a plastic film is applied on top of the tray in order to achieve airtight enclosure.

The overall quality of sealed paperboard trays has been linked to the utilised heat-sealing and press-forming parameters (Leminen *et al*. 2015a, 2017). A lower blank holding force in the press-forming process produced more durable paperboard trays for use in food processing compared to previous results (Niini *et al*. 2020a), whereas a higher blank holding force improved the quality of heat-sealed paperboard trays. (Leminen *et al*. 2015a)

In a previous study it was found that drying the trays, as compared to preconditioning, improved the durability of press-formed paperboard trays used for food processing (Niini *et al*. 2020b). More research on the effect of tray drying on the durability of press-formed paperboard trays used for food processing was needed to better quantify the advantage of drying trays before being used to heat foodstuff.

In this study, dimensional measurements of press-formed paperboard trays containing oatmeal were recorded during a two-stage food processing procedure. The two-stage procedure consisted of heating and cooling, with the empty trays being dried before being processed with foodstuff and the trays being heat-sealed before the cooling stage. Heat-sealing the trays after the heating stage and before the cooling stage was necessary to observe the behaviour of the press-formed and heat-sealed paperboard trays while used for food processing and to assess the combined effects of sealing and drying on the tray durability.

Displayed trends in the recorded dimension measurements highlighted the dimensional stability of the press-formed paperboard trays during food processing, which was used as an indicator of durability. Observing the influence of the food processing conditions was important to validate the sustained durability of the studied press-formed and heat-sealed paperboard trays while being utilised under standard food processing conditions.

Durability impacts from the food processing conditions were simulated with leak detection tests and optical analysis on the empty press-formed paperboard trays after being heated and cooled. Usage of the empty trays allowed for explicit focus on the impacts from the food processing conditions as the influence of the foodstuff was excluded.

EXPERIMENTAL

Materials

The material used with the press-formed paperboard trays was Stora Enso (Helsinki, Finland) Trayforma Performance 350 + 40 WPET, a commercial material coated with polyethylene terephthalate (PET). The chosen press-formed tray geometry was Gastonorm size GN1/4, a commonly used food container for applications with foodstuffs, with a reference dimension of 265 mm x 162 mm x 38 mm according to SFS-EN standard 631-1 (2013). The press-formed trays contained a standard amount of oatmeal in terms of food processing applications; 250 mL of water and 50 g of oat flakes were measured and placed into the trays before the heating stage of the food processing procedure.

A constant humidity chamber (at a relative humidity (RH) of 80%) was used to store the materials before die-cutting the tray blanks and press-forming the trays. Before the food processing procedure, the trays were stored in laboratory conditions at 22 °C and 10% to 15% RH. The moisture content of the press-formed trays was measured (a moisture content of 5.6%) with a PMB 53 Moisture Analyzer (Adams Equipment Oxford, CT).

For heat-sealing the trays, Flextrus Ecobar 23/70 Reseal APET was used as the film material, and the indicated film thickness of the lidding material was 115 µm. For the leak detection tests of the sealed trays, colouring solution was flushed into the trays. The utilised colouring solution contained 0.5 g of dyestuff E131 Blue dissolved in 100 mL of ethanol (96%), as set by EN standard 13676 (2001).

Methods

Manufacturing of the tray blanks was performed with a die cutter (LUT Packaging Line, Lappeenranta, Finland). Subsequent press-forming of the trays was finalized using the same machinery (LUT Packaging Line) with the press-forming parameters of a short production run to produce 18 trays under the following conditions: a 150 ºC female mould temperature, a 1 s dwell time, a 150 kN pressing force, a 0.96 kN blank holding force, and a 80 mm/s pressing speed. The press-formed trays were loaded with a standard amount of raw oatmeal for the initial tray measurements before being heated.

The tray dimension measurements were obtained with a quality monitoring system (part of the LUT Packaging Line), which consisted of a Cognex IS5605-11 smart camera and a backlit table. The tray dimensions were measured five times with six-minute intervals during both heating and cooling stages of the food processing procedure in order to observe trends in the dimensional stability of the recorded tray dimension measurements. Two trays underwent the food processing procedure at a time. Altogether 18 trays underwent the food processing procedure, consisting of three tray sets with six trays in each set. The tray sets are explained in Table 1.

Table 1. Compilation of Studied Tray Sets

Tray Set	Trays Dried Before the Heating	Trays Heat-Sealed Before the Cooling
Sealed + Dried	X	X
Dried	X	-
Ref	-	-

Drying of the trays was performed at a temperature of 225 ºC and a RH of 0% for 2 min using a commercial steam-combi oven Gaggenau BSP251110 (Munich, Germany). The measured moisture content of the dried trays was 0.88%. The trays were dried empty, and the oatmeal was loaded into the dried trays with minimal delay before starting the food processing procedure *via* heating the tray and oatmeal. Minimizing the delay between drying the trays and heating the trays was required to maintain the dryness of the trays, *i.e.*, preventing prolonged moisture re-absorption by the trays due to the laboratory conditions.

The trays were heated for 30 min at 225 °C and 80% RH using the Gaggenau BSP251110 steam-combi oven. After having been heated, the trays were cooled for 30 min at -26 °C in a commercial no-frost freezer with minimal delays between heating and cooling to simulate a production run of prepared food. The measured humidity conditions inside the used freezer was 20% to 25% RH. Differences in the ambient conditions between storing of the trays, as well as heating and cooling the trays, enabled observation of the tray performance when exposed to a cyclic environment during the food processing procedure.

The trays were heat-sealed with an Ilpra Speedy tray sealer (Mortara, Italy) using the heat-sealing parameters of a short production run to seal six trays of the related tray set (as listed in Table 1) with the following conditions: a sealing temperature of 190 °C, a sealing time of 2.5 s, and a sealing pressure of 6 bar. The heat-sealed trays were sealed after being heated but before being cooled, with minimal delay in between these procedures, to enable undisturbed food processing.

Leak detection tests were performed on empty press-formed trays heated at 140 °C, 170 °C, 200 °C, and 225 °C at 80% RH for 30 min after being heat-sealed to assess durability impacts from simulated food processing conditions in the heating stage. The impacts from the lower heating temperatures as well as a temperature of 225 °C utilised in the food processing procedure of the studied trays were compared to observe the limits of the paperboard trays during the heating stage. The press-forming of the empty trays before being heated and the heat-sealing of the empty trays after being heated was performed with uniform parameters and setup conditions, the same as the studied trays with oatmeal.

A colouring solution (as shown in Fig. 1) was used to detect leaks and pinholes in the empty trays caused by the food processing conditions. Colour changes in the paperboard material, along with the detected leaks and pinholes, were interpreted to indicate the durability limits of the press-formed paperboard trays in various food processing conditions.

Optical analysis was performed on the surface of the PET coating of the food processed trays from the cut tray samples. The samples were cut from the trays during different stages of the food processing procedure. Two tray samples were cut from the edge of the tray flange, one sample was cut from the longer side of the tray, and one was cut from the shorter side of the tray. Use of the tray flange samples was necessary to observe the durability impact on the PET-coating in the heat-sealed area of the utilised tray geometry, and to focus on the portion of the PET coating that had no contact with the oatmeal during the food processing procedure.

A scanning electron microscope (SEM) Hitachi SU3500 (Toyko, Japan) was used for the optical analysis. A wolfram filament and secondary electron (SE) detector were used for micro graphing of the samples, and the samples were Au/Pd target sputter-coated before their imaging. The utilised acceleration voltage was 5 kV and the working distance was set as 15.84 mm for the samples. The different tray samples analysed *via* SEM are listed below in Table 2.

Table 2. Tray Samples of Optical Analysis

Tray Edge Sample	Dried	Heated	Cooled
Heated	-	X	-
Heated + Cooled	-	X	X
Dried + Heated	X	X	-
Dried + Heated + Cooled	X	X	X
Dried	X	-	-
Ref	-	-	-

Fig. 1. Pinholes (left) and corner creases leaks (right) highlighted with arrows on bottom and top of sealed trays

RESULTS AND DISCUSSION

Dimension Measurements

The displayed tray dimension measurements are averages of all six trays from their respective tray sets (as shown in Table 1). The tray width in the measurements refers to the shorter sides of the tray, with the machine direction of the material fibres being parallel to the longer side. The focus of the presented dimension measurements was on tray width, as major trends in the dimension measurements were primarily observed to affect the tray width (as shown in Fig. 2).

Fig. 2. Impact of tray flange distortion on tray width

Heating the trays resulted in a smaller width distortion in the trays that were dried (as shown in Fig. 3), whereas cooling the heat-sealed trays resulted in only a minor width distortion (as shown in Fig. 4). Consistent with a previous study (Niini *et al*. 2020b), drying the empty trays resulted in a decreased tray width due to the shrinkage of paperboard fibres during the drying process.

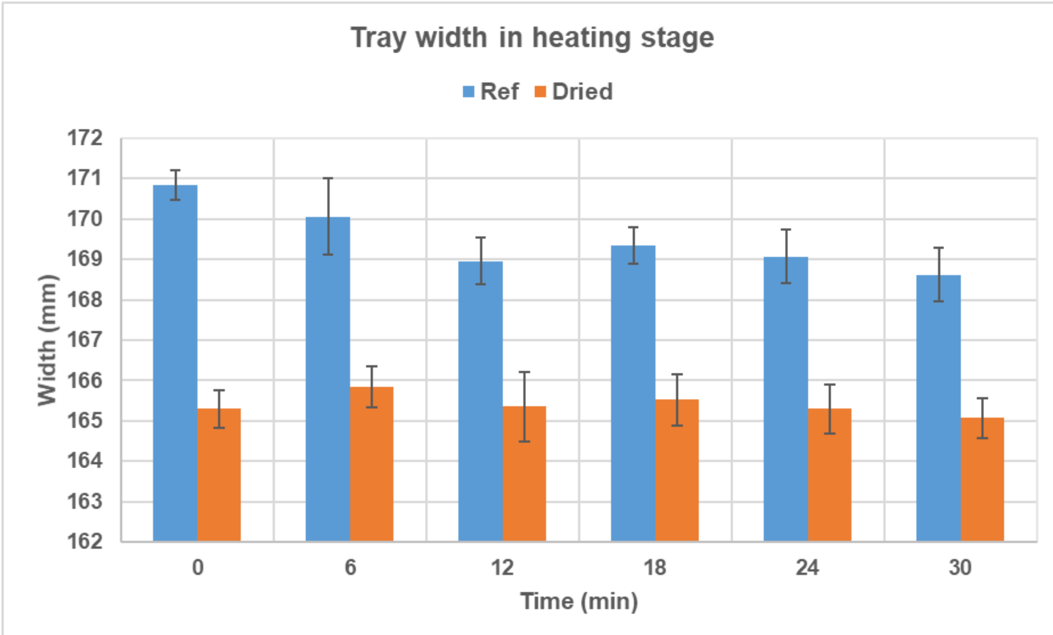

Fig. 3. Tray dimension measurements during the heating stage of the food processing procedure

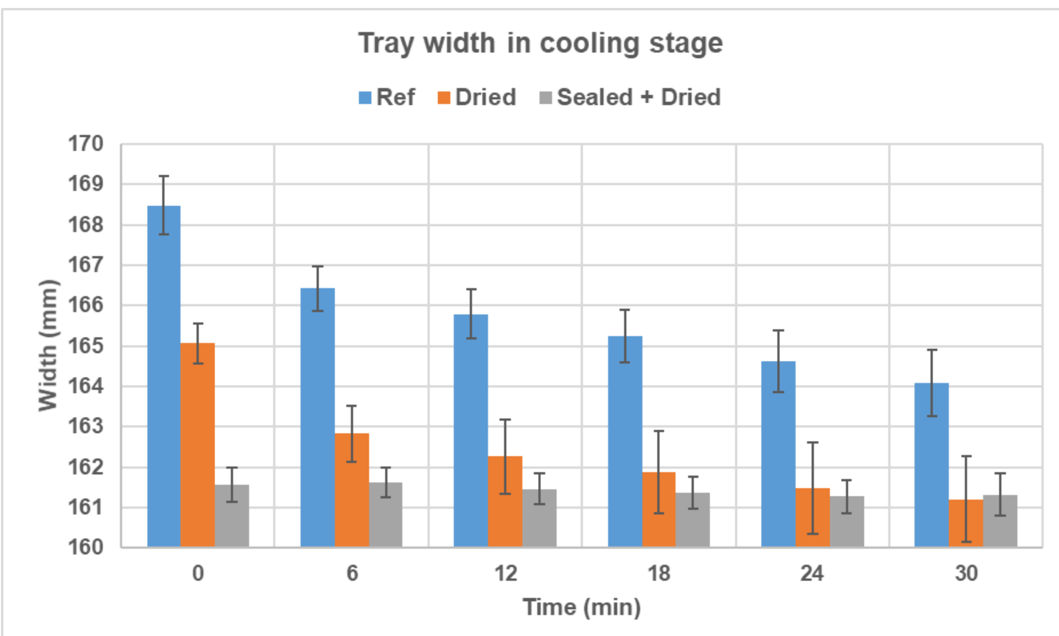

Fig. 4. Tray dimension measurements during the cooling stage of the food processing procedure

The recorded initial tray width (165 mm) for the dried tray samples and the width of the reference tray (171 mm) were notably larger in comparison to the standard width of a GN1/4 tray (162 mm). Differences between the standard tray width and the width of the studied trays could be explained in part by the utilised press-forming parameters, as well as by the weight of the oatmeal in the trays.

In a previous study, the use of a higher forming tool temperature (180 °C) in the press-forming process of GN1/4 paperboard trays resulted in a smaller difference between the measured widths and the standard tray widths (Niini *et al*. 2020a). The implicated effect from the weight of oatmeal on the width of the tray was due to the tray being loaded with raw oatmeal before the initial dimension measurements; the load of the oatmeal thereby being apparent in the measured tray width.

The relative width changes after the different stages of the food processing procedure (as shown in Fig. 5) validated the advantages of the dried tray samples during the heating stage whilst highlighting the dimensional stability of the heat-sealed trays during the cooling stage.

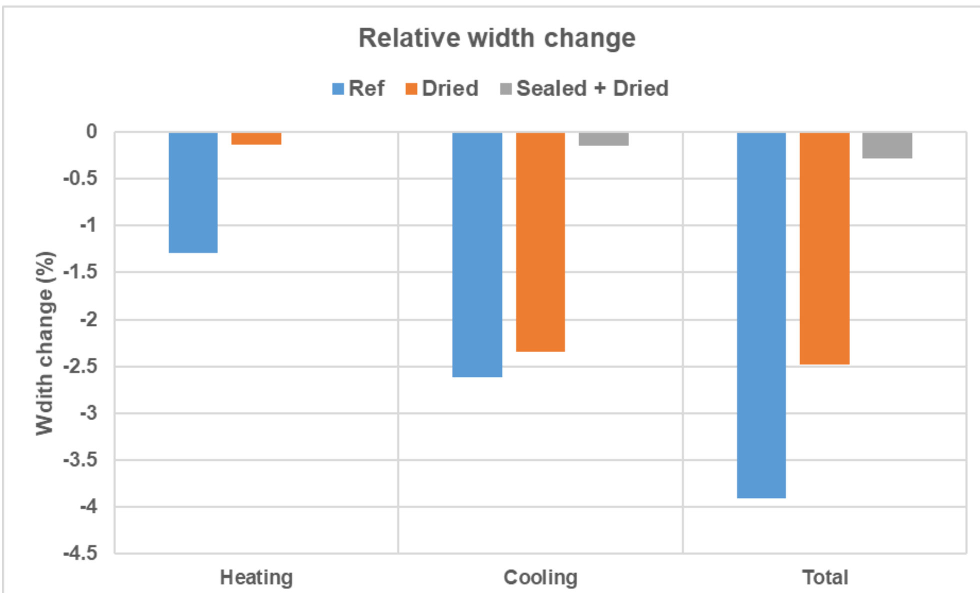

Fig. 5. Relative width changes during the food processing procedure

The combined effects from drying and sealing strengthened dimensional stability. Moisture absorption was observed to negatively affect the mechanical performance of paperboard food packages, which was consistent with previous research by Rhim *et al*. (2010). The stiffness degradation and material curling caused by hydroexpansion in the paperboard fibres, due to material moisture absorption during the food processing, was observed as a decrease in the tray width. Drying the trays mitigated the moisture absorption induced effects in the trays primarily during the heating stage of food processing procedure, thus providing only a limited solution for sustained tray durability.

Limiting the moisture absorption induced effects *via* material drying cannot effectively prevent creep and release of dried-in stresses in the trays during the cooling stage of the food processing procedure, as the results showed only a minor difference in the dimensional stability of the reference trays as compared to the dried trays during the cooling stage. The results showed heat-sealing as a potential solution to reinforce the advantages of drying the trays, *i.e.*, in curbing the material curling and stiffness degradation during food processing procedure of press-formed paperboard trays.

Heat-sealing effectively minimized changes in the tray width during the cooling, which suggested an enhanced tray rigidity from the applied PET film. The film was observed to keep the press-formed tray geometry intact, *i.e.*, reducing material curling and stiffness degradation, implying the seal strength was sufficient to sustain deforming forces on the tray flange during the cooling stage.

The creep and release of dried-in stresses in the trays during the cooling stage were considered dependent on the press-formed tray geometry that was used, the food processing conditions in the cooling stage, the fibre machine direction, and the foodstuff used. Consequently, seal strength was considered dependent on the utilised sealing parameters, the film material, and the coating of the trays in addition to the impacts from the food processing conditions during the heating stage.

Due to the many parameters involved that were not considered by the scope of this study, the seal strength of the PET film in press-formed paperboard trays could not be guaranteed to eliminate stiffness degradation and material curling in applications with demanding environmental conditions. More research is needed to study the limits and capabilities of curbing moisture absorption induced effects with press-formed and heat-sealed paperboard trays.

Leak Tests

Flushing of colouring solution into the empty trays heated with different temperatures resulted in leaks being detected at the corner creases of the trays (as shown in Fig. 6). Leaks were also detected at the corner edges of the trays when heated at a temperature of 225 °C.

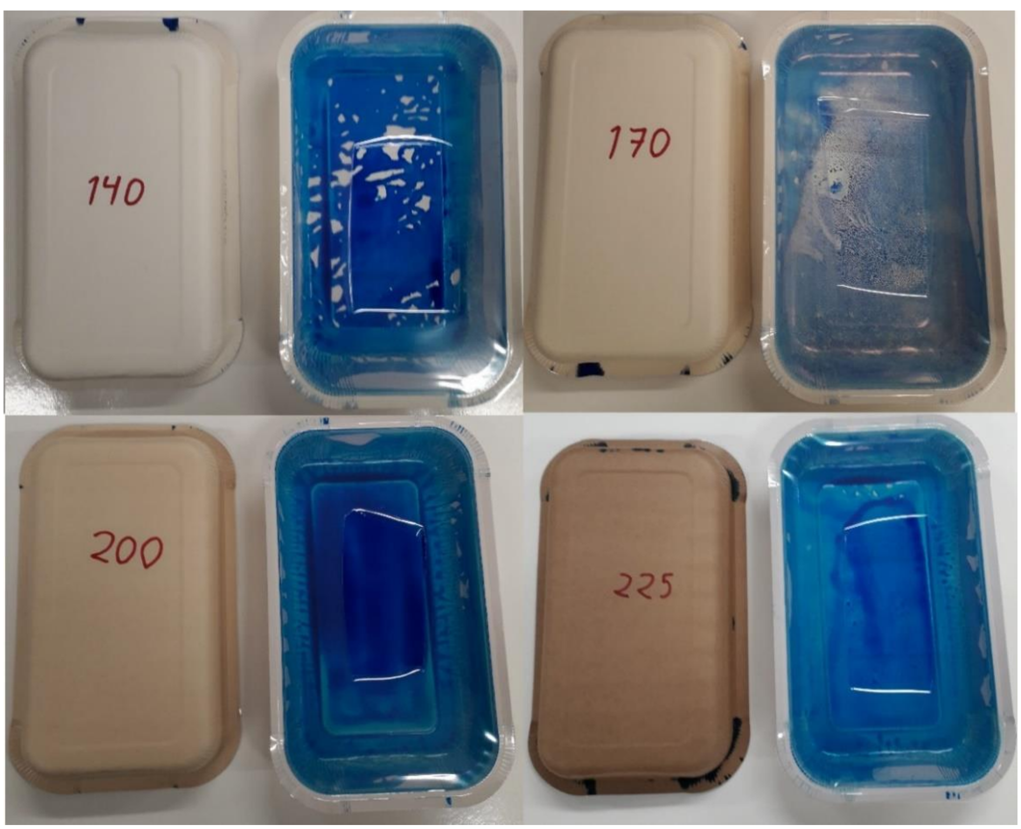

Fig. 6. Leak tests after heating the empty trays (indicated heating temperature is in °C)

Exposure of the empty trays to being heated resulted in a negative impact on the tray durability, as observed with the noticeable leaks. The colour change in the material of the trays indicated a less severe impact on durability when a lower heating temperature was used in the heating stage. The results point to a necessary use of lower heating temperature, *i.e.*, lower than 225 °C, during the heating process of the studied trays.

Additional leak tests performed on the dried tray samples showed minor leaks on the tray creases (as shown in Fig. 7). Based on the leak test results of the dried tray samples, a negative durability impact was connected to drying the trays, even before the food processing procedure with the oatmeal. Use of a lower heating temperature and longer heating time during the drying process of the press-formed paperboard trays was deemed necessary to achieve a lower moisture content in the dried tray samples with smaller effects on their heat-sealing properties.

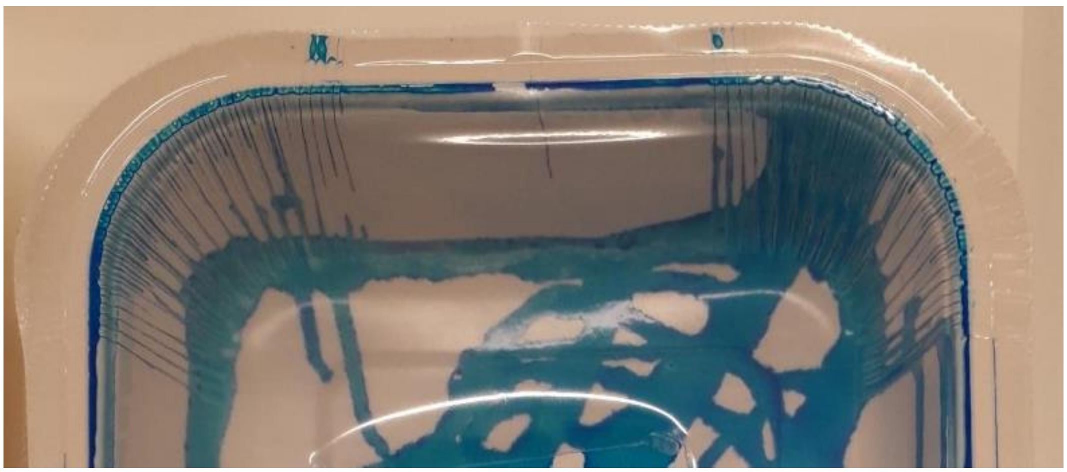

Fig. 7. Corner crease leaks on dried trays

Fig. 8. Leak tests of the empty trays before being heated

Leak test results performed on the empty trays before being heated showed no seal leaks on the trays (as shown in Fig. 8). The leaks detected on the heated empty trays were connected to the food processing conditions in the heating stage due to the trays showing no leaks before being heated. Improving the bonding of the PET film with the PET coating of the trays was considered essential to further the advantages gained from sealing the tray.

The simulated food processing conditions of the heating stage involved the use of heating temperatures well above the glass transition temperature of *ca.* 70 °C of the PET coating of the trays, with the ensuing crystallization of the molecular chains in the PET occurring until the melting point of *ca.* 255 °C (Jog 1995). The outcome of the leak tests suggested a link between the crystallization in the PET coating during the heating stage and the weakened bonding with the PET film in the heat-sealing stage after the heating.

The detected leaks appeared less severe in the dried tray samples, due to a smaller degree of crystallization occurring during the drying of the trays; the PET coating had a shorter exposure time to temperatures above the material glass transition temperature. In contrast, the detected leaks in the heated empty trays showed consistent corner crease leaks with no noticeable differences in severity of the leaks between the tested heating temperatures.

Previous research about the crystallization characteristics of heat-sealed high-density polyethylene films attributed a higher crystallinity in the films to a longer required heat-seal time (Miyata *et al*. 2014). Based on the results from this study, the weakened bonding in the sealing of the PET coated trays can be attributed to the crystallization in the PET coating during the heating process of the trays. The utilised heat-sealing parameters were not modified before the leak tests and, therefore, more testing is needed to study how to mitigate the weakened bonding *via* adjustment of the heat-sealing parameters for different degrees of crystallinity in PET coated paperboard trays.

Optical Analysis

Optical analysis on the surface of the PET coating of the tray samples showed a similar contrast between the surface morphology of the tray samples from different stages of the food processing procedure and the reference tray sample taken before either the drying or food processing (as shown in Fig. 9).

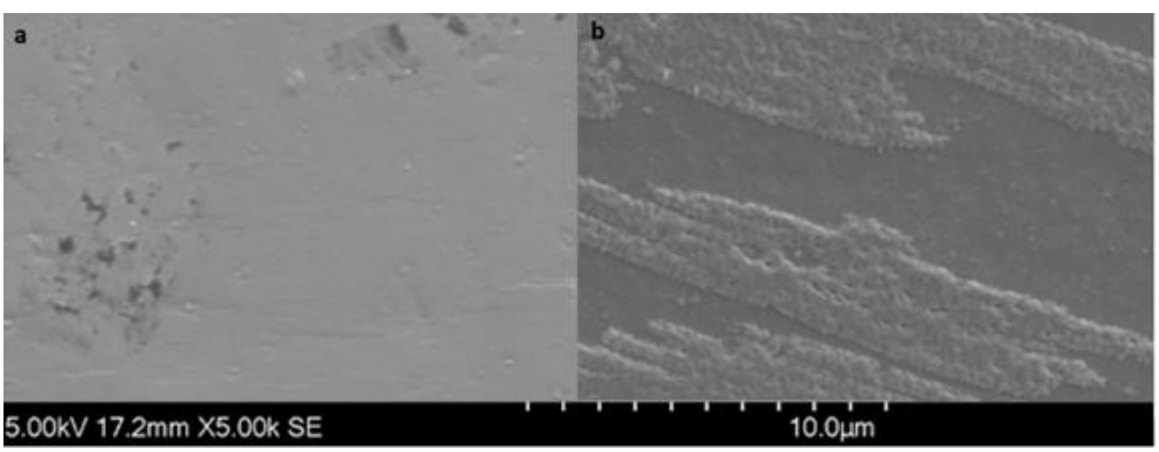

Fig. 9. Surface morphology of the PET coating (a) before and (b) after the food processing procedure

Scanning electron microscopy images of the food processed tray samples highlighted the whitened irregular areas on the PET coating, which were identified as crystalline particles. The crystalline particles were observed on the tray samples after both the heating and cooling stages of the food processing procedure, as well as in the dried tray samples (as shown in Fig. 10).

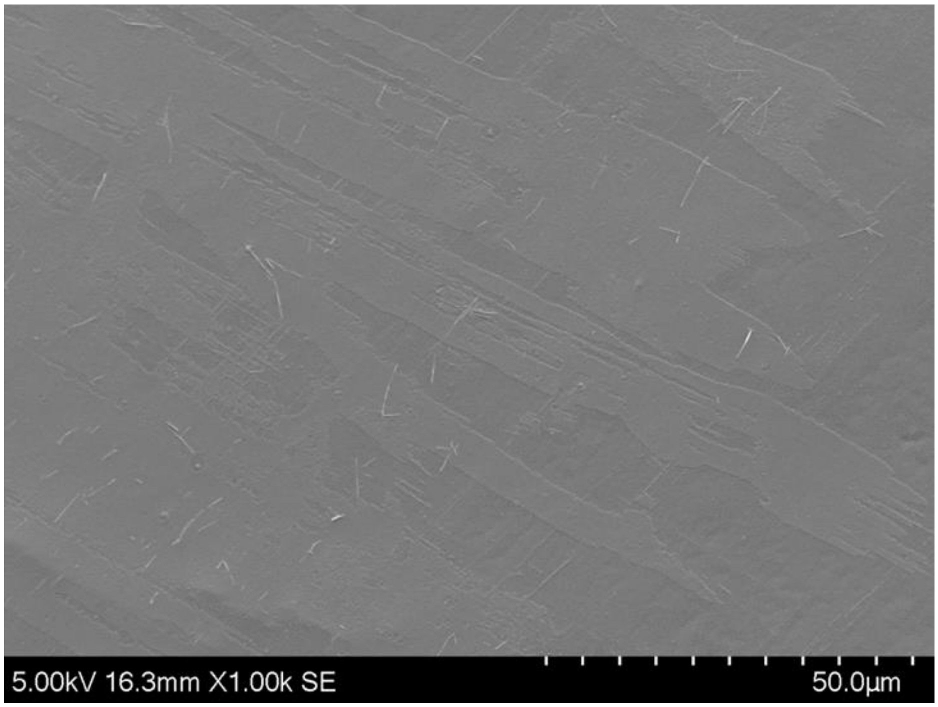

Fig. 10. Surface morphology of the PET coating after drying the tray

The SEM images of the food processed tray samples highlighted areas of crystal growth on the surface morphology of the PET coating. In line with findings from previous research by Ohishi *et al*. (2020), the noticeable growth of the crystalline particles on the PET surface morphology was connected to a prolonged exposure of the material to temperatures above its glass transition temperature.

The observed crystal growth supported the stated negative impact of PET crystallization on the heat-sealing properties of the empty heated trays, based on the leak test results. Consistent with other studies (Leminen *et al*. 2015a,b), the results of the optical analysis and leak tests connected the aggravated heat-sealing properties in press-formed paperboard trays to a lowered surface quality of PET coatings.

The results of the optical analysis, together with the conducted leak tests, validated the negative durability impact the food processing conditions had on the durability of press-formed paperboard trays. In addition, the crystal growth that occurred on the PET coating while heating the trays limited the usage of the press-formed paper trays in applications with demanding environmental conditions. Exploiting the drying and sealing processes for their combined beneficial effects in terms of the food processing of press-formed paperboard trays requires a compromise between the desired heat-sealing properties and the food processing conditions.

CONCLUSIONS

1. Press-formed paperboard trays, which were food processed with oatmeal, exhibited improved durability due to the combined benefits of the drying and sealing, *i.e.*, improving the dimensional stability of the trays compared with the reference trays. Drying the trays improved the dimensional stability during the heating stage, and heat-sealing improved the dimensional stability during the cooling stage.
2. Leak tests using a colouring solution with the empty heat-sealed trays simulated the negative impact of the utilised food processing conditions on the tray durability. Optical analysis on the surface of the poly(ethyleneterephthalate) (PET) coating of the trays validated the negative impact was caused by PET crystallization.
3. The PET crystallization was connected to heat exposure from the food processing procedure, which resulted in weakened heat-sealing properties in the trays. More research on the adjustment of the heat-sealing parameters and food processing conditions for the durability optimization of press-formed paperboard trays undergoing food processing was deemed necessary.

REFERENCES CITED

EN 13676 (2001). "Polymer coated paper and board intended for food contact – Detection of pinholes," European Committee for Standardization, Brussels, Belgium.

Jog, J. P. (1995). "Crystallization of polyethyleneterephtalate," *Journal of Macromolecular Science, Part C* 35(3), 531-553. DOI: 10.1080/15321799508014598

Leminen, V., Mäkelä, P., Tanninen, P., and Varis, J. (2015b). "Methods for analyzing the structure of creases in heat sealed paperboard packages," *Journal of Applied Packaging Research* 7(1), 49-60. DOI: 10.14448/japr.03.0005

Leminen, V., Pesonen, A., Tanninen, P., and Varis, J. (2017). "Effect of elevated heat sealing pressure on the gas tightness of press-formed paperboard trays," *BioResources* 12(4), 8359-8367. DOI: 10.15376/biores.12.4.8359-8367

Leminen, V., Tanninen P., Lindell, H., and Varis, J. (2015a). "Effect of blank holding force on the gas tightness of paperboard trays manufactured by the press forming process," *BioResources* 10(2), 2235-2243. DOI: 10.15376/biores.10.2.2235-2243

Marin, G., Nygårds, M., and Östlund, S. (2020a). "Stiffness and strength properties of five paperboards and their moisture dependency," *TAPPI Journal* 19(2), 71-85. DOI: 10.32964/TJ19.2.71

Marin, G., Nygårds, M., and Östlund, S. (2020b). "Elastic-plastic model for the mechanical properties of paperboard as a function of moisture," *Nordic Pulp & Paper Research Journal* (in press), 1-9. DOI: 10.1515/npprj-2019-0104

Miyata, K., Ozama, T., Nishioka, A., Koda, T., and Murasawa, G. (2014). "The relationships between crystallization characteristics and heat-sealing properties of high-density polyethylene films," *Journal of Plastic Film and Sheeting* 30(1), 28-47. DOI: 10.1177/8756087913487542

Niini, A., Leminen, V., Tanninen, P., Varis, J. (2020a). "Effect of press-forming parameters on dimensional stability of paperboard trays," *Packaging Technology and Science,* Manuscript submitted.

Niini, A., Leminen, V., Tanninen, P., Varis, J. (2020b). “Humidity effect in heating and cooling of press-formed paperboard food packages: Comparison of storing and heating conditions,” *Packaging Technology and Science*, Manuscript submitted.
Ohishi, T., Ichikawa, K., Isono, S. (2020). “Heat-resistant properties of a SiO_2-coated PET film prepared by irradiating a polysilazne-coated film with excimer light,” *Materials Sciences and Applications* 11(1), 58-69. DOI: 10.4236/msa.2020.111005
Rhim, J-W. (2010). “Effect of moisture content on tensile properties of paper-based food packaging materials,” *Food Science and Biotechnology* 19, 243-247. DOI: 10.1007/s10068-010-0034-x
SFS-EN 631-1 (2013). “Materials and articles in contact with foodstuffs. Catering containers. Part 1: Dimensions of containers,” Finnish Standards Association, Helsinki, Finland.

Article submitted: August 31, 2020; Peer review completed: October 25, 2020; Revised version received and accepted: November 5, 2020; Published: November 13, 2020.
DOI: 10.15376/biores.16.1.236-248