Effects of Press-forming Parameters on the Dimensional Stability of Paperboard Trays

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The dimensional stability of press-formed paperboard trays was investigated during heating and cooling of trays packed with oatmeal. Female mold tool temperature, dwell time, pressing force, and blank holding force were altered in the press-forming of the trays to observe their impacts on the dimensional stability. Dimensional measurements of the trays showed reduced tray width, and the trays exhibited distortions on the tray flange and outer wall. The results showed smaller effects on the tray length, parallel to the machine direction of the material. Improved dimensional stability of the trays was found with a 180 °C female mold tool temperature, a 600-ms dwell time, a 150-kN pressing force, and a 1.44-kN blank holding force. The optimal press-forming parameters were concluded to enhance bonding of the paperboard fibers during the press-forming. The optimization of the press-forming parameters was found necessary to reduce the observed negative response of the material to the challenging environmental conditions in the production of prepared food.

Keywords: Food container; Mold temperature; Dwell time; Pressing force; Blank holding force; Curling

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INTRODUCTION

Paperboard packages are affected by the environmental conditions present during manufacturing, handling, and usage due to their moisture sensitivity. Humidity-induced curling in paperboard has been observed, and increased moisture content of the material has been connected to decreased dimensional stability of press-formed trays (Ovaska *et al*. 2018a).

Curling of paperboard during moisture absorption is induced by hygroexpansion of the material fibers (Lindner 2018). Plastic-coated paperboard can have a varying response to curling depending on the hygroscopic properties of the coating. Paperboard coatings can be used to mitigate the moisture absorption of paperboard by improving the water resistance of the material (Rhim *et al*. 2007).

Press-forming parameters affect the dimensions and quality of paperboard trays (Tanninen *et al*. 2018). Heat input in the manufacturing of paperboard trays has a major impact on the tray quality (Leminen *et al*. 2016). High female mold tool temperature improves the dimensional accuracy and formability of press-formed paperboard trays (Ovaska *et al*. 2018b), and high forming tool temperature enhances the dimensional accuracy of deep-drawn paperboard cups (Wallmeier *et al*. 2016). Increased heat input induces shrinking of paperboard fibers by moisture desorption, enabling improved rigidity and dimensional accuracy in the manufacturing of paperboard trays.

Dwell time, female tool temperature, and pressing speed are among the heat-related press-forming parameters that can be utilized to modify the outer dimensions of the tray to achieve the desired dimensional accuracy. Other press-forming parameters such as blank holding force and pressing force only have limited effects on the tray dimensions, yet they are important in achieving trays of desirable quality (Tanninen *et al*. 2016).

Optimized design of package vent areas mitigates the negative effects of environmental conditions on the stiffness of paperboard packages (Fadiji *et al*. 2019). The effects of press-forming parameters to the dimensional stability of paperboard trays have not been studied before. Optimized press-forming of paperboard trays is needed to improve the dimensional stability of paperboard packages in applications requiring exposure to demanding environmental conditions.

This research investigated how press-forming parameters affect the dimensional stability of paperboard trays. The trays were heated and cooled with oatmeal to observe the dimensional stability in the experimental setup with challenging environmental conditions. The heating and cooling parameters were adjusted to represent the production of prepared food.

EXPERIMENTAL

Materials

The experimental paperboard material was Stora Enso (Helsinki, Finland) Trayforma Performance 350 + 40 WPET. The material is extrusion-coated with polyethylene terephthalate (PET). The material baseboard contains a chemi-thermomechanical pulp (CTMP) middle layer, a solid bleached sulfate (SBS) top layer, and an SBS bottom layer. The PET grammage of the material was 40 g/m^2, and the thickness of the PET coating was 15 µm. The baseboard grammage was 350 g/m^2, and the thickness was 460 µm (Stora Enso 2020).

A constant humidity chamber at 80% relative humidity (RH) was used to store the materials before die-cutting of tray blanks. The tray blanks were pre-conditioned at 23 °C and 80% RH before press-forming of the trays. The press-formed trays were kept in laboratory conditions at 22 °C and 10% to 15% RH before their packing with oatmeal. A standard amount of the oatmeal was packed into the trays, containing 50 g of oat flakes and 250 mL of water.

Methods

Die-cutting of the tray blanks and press-forming of the trays were performed using an LUT Packaging Line (Lappeenranta, Finland) apparatus. The die-cutting and press-forming of the trays simulated realistic manufacturing of paperboard food containers. The tested tray geometry was a standard Gastronorm size GN 1/4, a food container commonly used with prepared food, with its reference dimensions specified according to the SFS-EN 631-1 standard (2013) as 265 mm × 162 mm × 38 mm. The tray blanks were die-cut with the longer side of the blank being parallel to the machine direction of the material.

The female mold tool temperature, dwell time, pressing force, and blank holding force were altered during the press-forming of the trays (Fig. 1). The LUT Packaging Line was operated in laboratory conditions at 22 °C and 10% to 15% RH. Manufacturing of the trays from the conditioned material was done with a minimal delay. The press-forming process was previously explained in detail by Tanninen *et al.* (2016).

A set of three trays was manufactured for each configuration of the altered press-forming parameters (Table 1). Pressing speed was kept constant at 80 mm/s during the press-forming. The male mold tool was unheated to avoid damage to the PET coating. No cracks or defects were detected in the manufactured trays by a visual inspection.

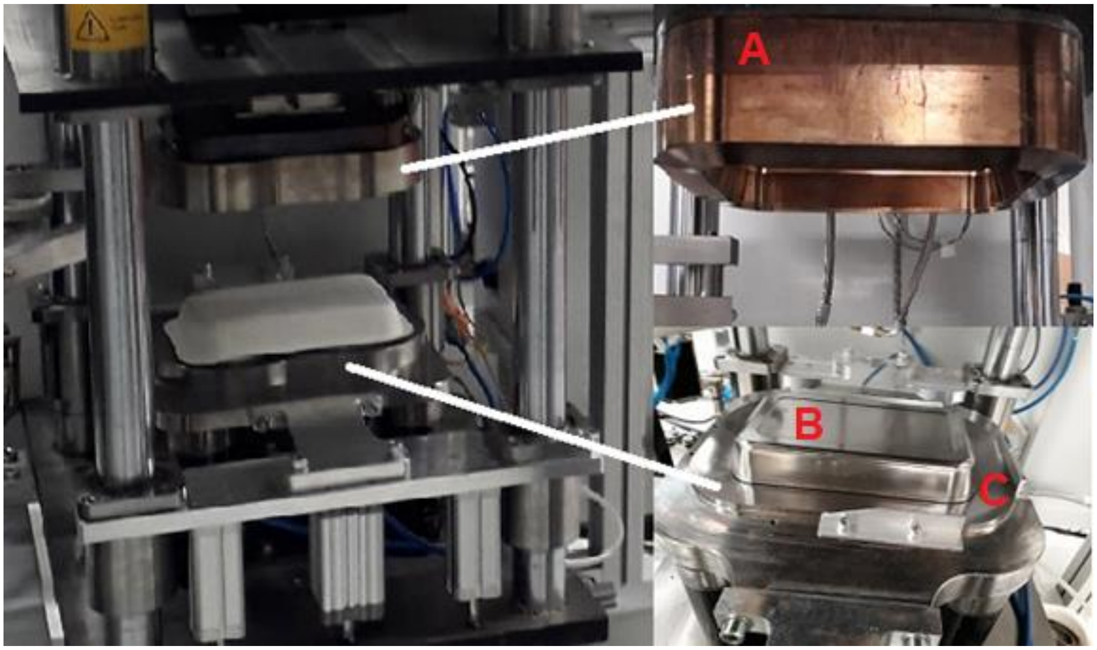

Fig. 1. Tray manufacturing apparatus: (A) female tool, (B) male tool, and (C) blank holder

Table 1. Press-forming Parameters

Female Mold Tool Temperature (°C)	Dwell Time (ms)	Pressing Force (kN)	Blank Holding Force (kN)
60	600	75	1.44
			2.88
		150	1.44
			2.88
	1600	75	1.44
			2.88
		150	1.44
			2.88
120	600	75	1.44
			2.88
		150	1.44
			2.88
	1600	75	1.44
			2.88
		150	1.44
			2.88
180	600	75	1.44
			2.88
		150	1.44
			2.88
	1600	75	1.44
			2.88
		150	1.44
			2.88

The dimensions of the trays were measured using a quality monitoring system (part of the LUT Packaging Line). The monitoring system consisted of a backlit table and a Cognex IS5605-11 smart camera (Fig. 2A) taking images above the table to display accurate dimensions of the trays (Fig. 2B). System software of the monitoring setup automatically calculated the dimensions, and the smart camera was calibrated for the tray geometry (Fig. 2C) to take images 650 mm above the table. Previous testing on the accuracy of the monitoring system showed a 0.05 mm standard deviation with the measured dimensions (Tanninen *et al*. 2016).

Reference widths and lengths of the trays were measured after the trays were packed with the oatmeal. The dimensional measurements were performed at 10-min intervals, once after the heating and thrice during the cooling, totaling five measurements with the reference measurement included.

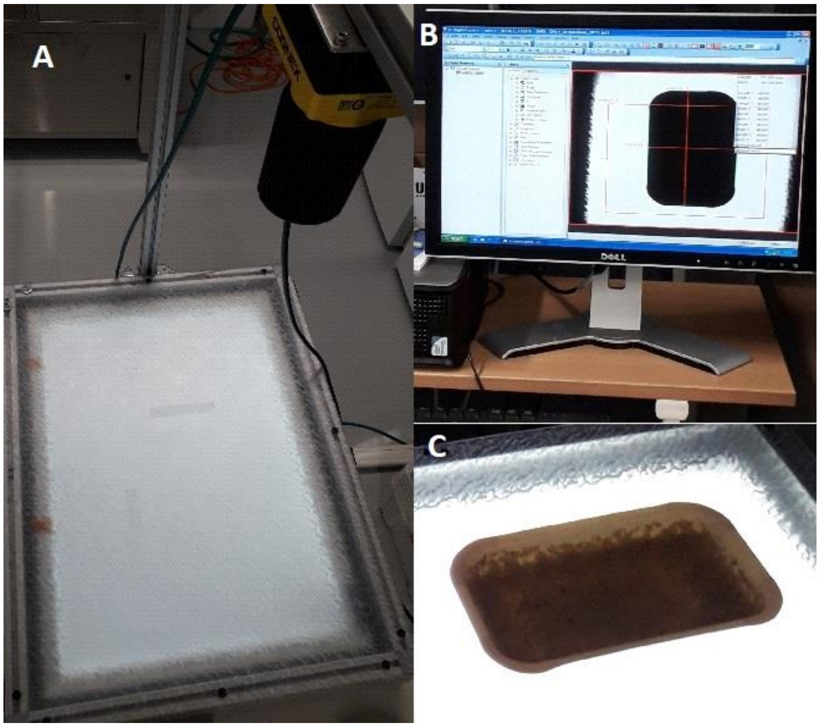

Fig. 2. (A) Monitoring system setup, (B) display of tray dimensions, and (C) the tray on the backlit table for dimensional measurements

The trays were heated at 185 °C and 100% RH for 10 min in a Gaggenau BSP251110 combi-steam oven (Munich, Germany). The high heating humidity was selected to signify the material response in the experiments. Two trays were heated and cooled at a time due to the limited capacity of the utilized equipment. The trays were cooled in a commercial no-frost freezer at -26 °C for 30 min following the heating.

The trays were cooled on the highest level of the freezer located closest to the freezer fan to allow efficient defrosting during the cooling. The cooling temperature and time were selected to reach an oatmeal temperature of 6 °C after the cooling as set by the SFS-EN 12571 standard (2012). The oatmeal temperature was measured with a digital thermometer from the middle of the tray. Oatmeal was selected as a filling for the trays to represent hot ready meals due to its homogeneity and accurately reproducible cooking process.

The trays were heated and cooled without a lidding film. Flow-pack sealing of the trays following the cooling was excluded from the scope of this study.

RESULTS AND DISCUSSION

All displayed measurements are averages of the three trays for each configuration (Table 1) of the studied press-forming parameters. Tray width was interpreted as parallel to the shorter side of the tray, and tray length was interpreted as parallel to the longer side of the tray.

Heating

Dimensional changes during the heating were detected visually as curling of the material in the form of distortion of the tray flange (Fig. 3) on the longer side of the tray. The upright springback of the tray flange reduced the tray width, as the tray dimensions were measured from above.

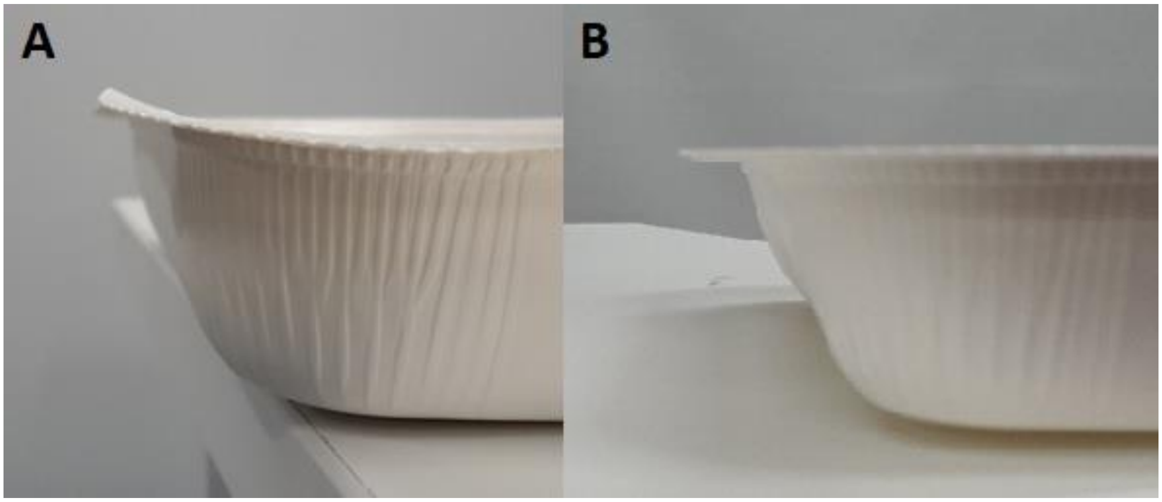

Fig. 3. Distortion of tray flange on the longer side of the tray (A) after heating compared to (B) reference

The changes in the tray length were visually undetectable. The results from the monitoring system showed larger changes in the tray width (Fig. 4). The larger dimensional changes in the tray width were linked to the fiber direction of the material. Moisture absorption in paperboard occurs with different gradients for the cross and machine directions of the paperboard fibers (Bosco *et al*. 2018). Swelling and shrinking of paper substrates in the paperboard occur likewise with different gradients (Bosco *et al*. 2018).

Unequal swelling of the fibers in the paper substrate of the material baseboard was linked to the observed dimensional changes. Swelling of the paperboard fibers from excessive moisture absorption results in hygroscopic strains to the fibers, and the hygroscopic strains are linearly dependent on the moisture content change of the material (Niskanen *et al*. 1997). The reduced dimensional stability of the trays suggested moisture content changes during the heating. The press-forming parameters, conditioning of the trays, and the heating conditions were identified as factors affecting the material moisture content.

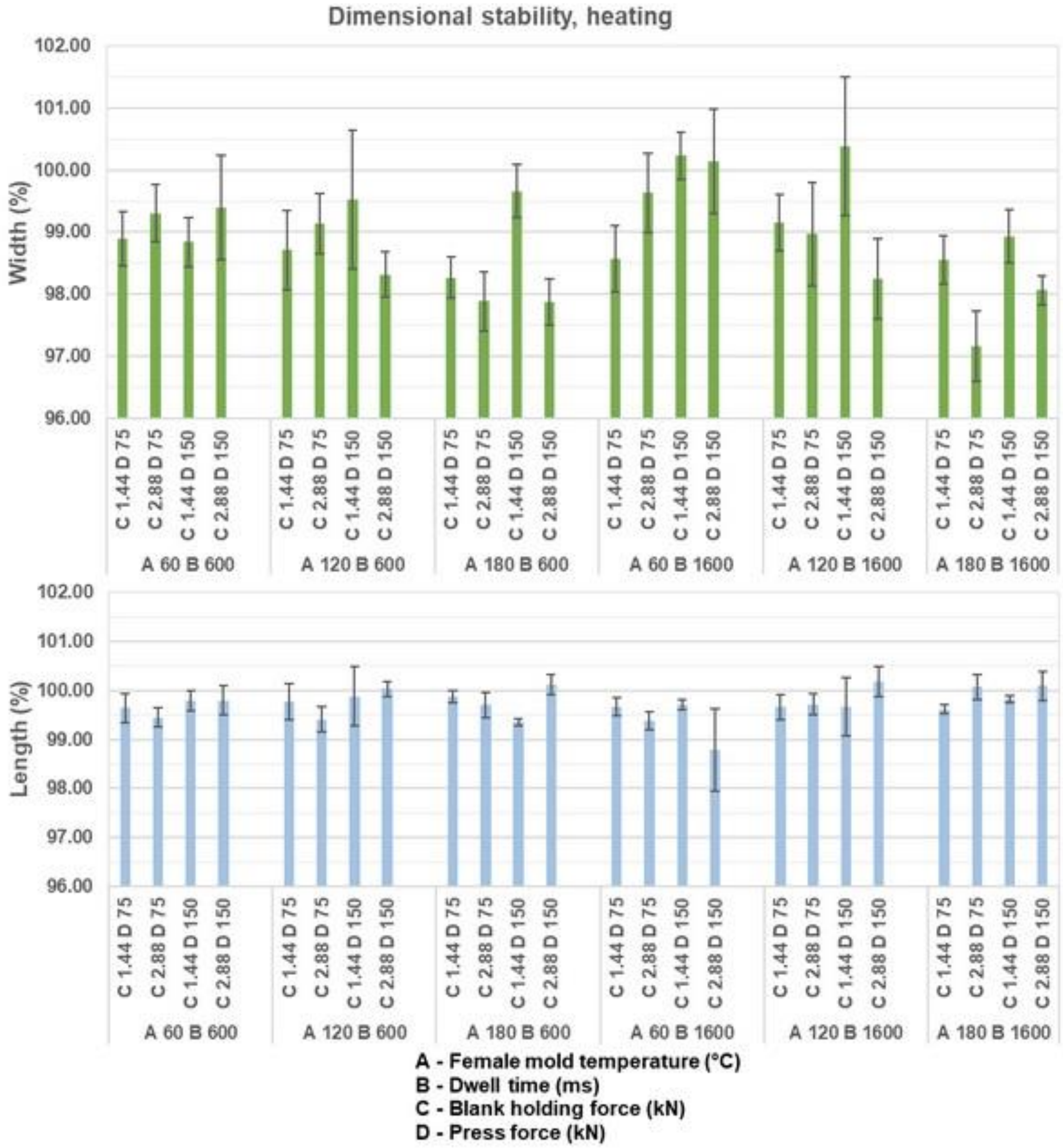

Fig. 4. Dimensional stability of trays after the heating

Of the studied press-forming parameters, the 1600-ms dwell time and 180 °C female mold tool temperature amplified the material moisture desorption during the tray manufacturing. High tool temperature and long dwell time cause drying of paperboard in press-forming, and increased dwell time decreases the moisture content of press-formed paperboard trays (Tanninen *et al*. 2016). The moisture content of the heated trays was consequently assumed to vary depending on the studied press-forming parameters. The varying moisture content and the fiber direction of the material influenced the effects of the press-forming parameters to the tray width and length.

The trays manufactured using the 1.44-kN blank holding force and 180 °C tool temperature showed smaller decreases of the tray width. The blank holding force is the key press-forming parameter in achieving flatness of the tray flange, and a larger blank holding force applied on the tray blank provides a flatter tray flange (Leminen *et al*. 2015). The trays manufactured using the 2.88-kN blank holding force exhibited a more rigid and flatter tray flange.

Stress relaxation in the paperboard geometry after moisture content change of the material has been connected to exposure to different RH levels (Leppänen *et al*. 2017). Tray width reduction in the form of tray flange distortion implied stress relaxation in the tray flange in the cross direction of the material. The larger width reductions of the trays manufactured with the 2.88-kN blank holding force reinforced the finding about the material stress relaxation in the cross direction.

The trays manufactured with the 150-kN pressing force, 1600-ms dwell time, and 180 °C tool temperature showed smaller decreases of the tray length. Increased pressing force, dwell time, and female tool temperature in the press-forming of paperboard trays previously resulted in decreased tray dimensions and increased tray rigidity (Tanninen *et al*. 2016). The trays press-formed with the 150-kN pressing force, 1600-ms dwell time, and 180 °C tool temperature displayed the smallest reference dimensions and were assumed to be the most rigid. Smaller length changes of the trays with the more rigid and flatter tray flanges suggested a positive impact of tray rigidity to the dimensional stability of the trays in the machine direction of the material.

Baking expansion of the oatmeal influenced the measurements during the heating, partly explaining the observed deviation in the results. The oatmeal was identified as an alternative source of moisture to the material. The number and direction of the creases affects quality of the tray corners (Tanninen *et al.* 2015). A possible link between the quality of the tray corner and the tray flange distortion was recognized. Additional testing is needed to investigate the role of creases to the dimensional stability.

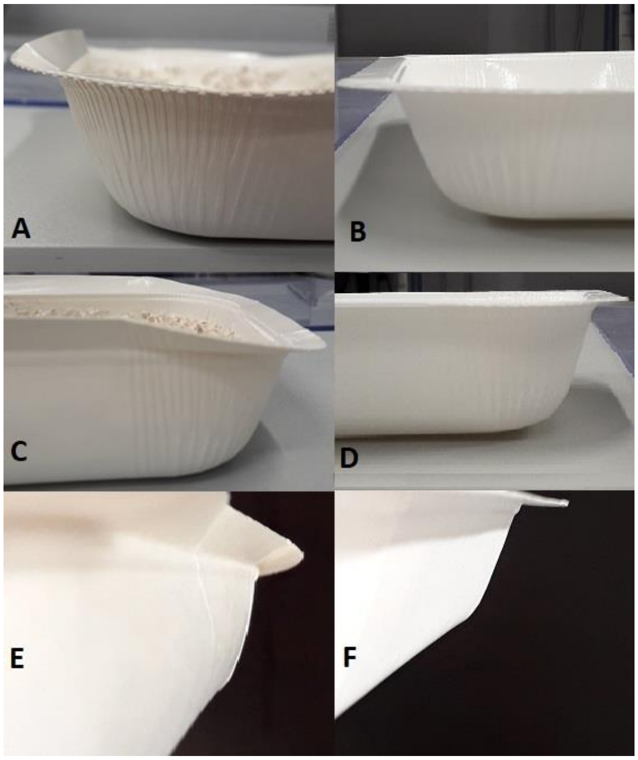

Fig. 5. Tray flange (A) after cooling compared to (B) reference, tray corner (C) after cooling compared to (D) reference, and tray wall (E) after cooling compared to (F) reference

Cooling

The material curling was exacerbated during the cooling, as observed visually on the flange (Fig. 5A and 5B), corner (Fig. 5C and 5D), and wall (Fig. 5E and 5F) of the longer side of the tray.

The monitoring system detected the width changes from the tray flange, and the observed width distortions on the tray corner and wall were only detected visually. The tray flange distortion during the cooling was indicative of the tray wall and corner distortions. Larger tray width reductions corresponded with visually noticeable distortion of the tray wall and corner.

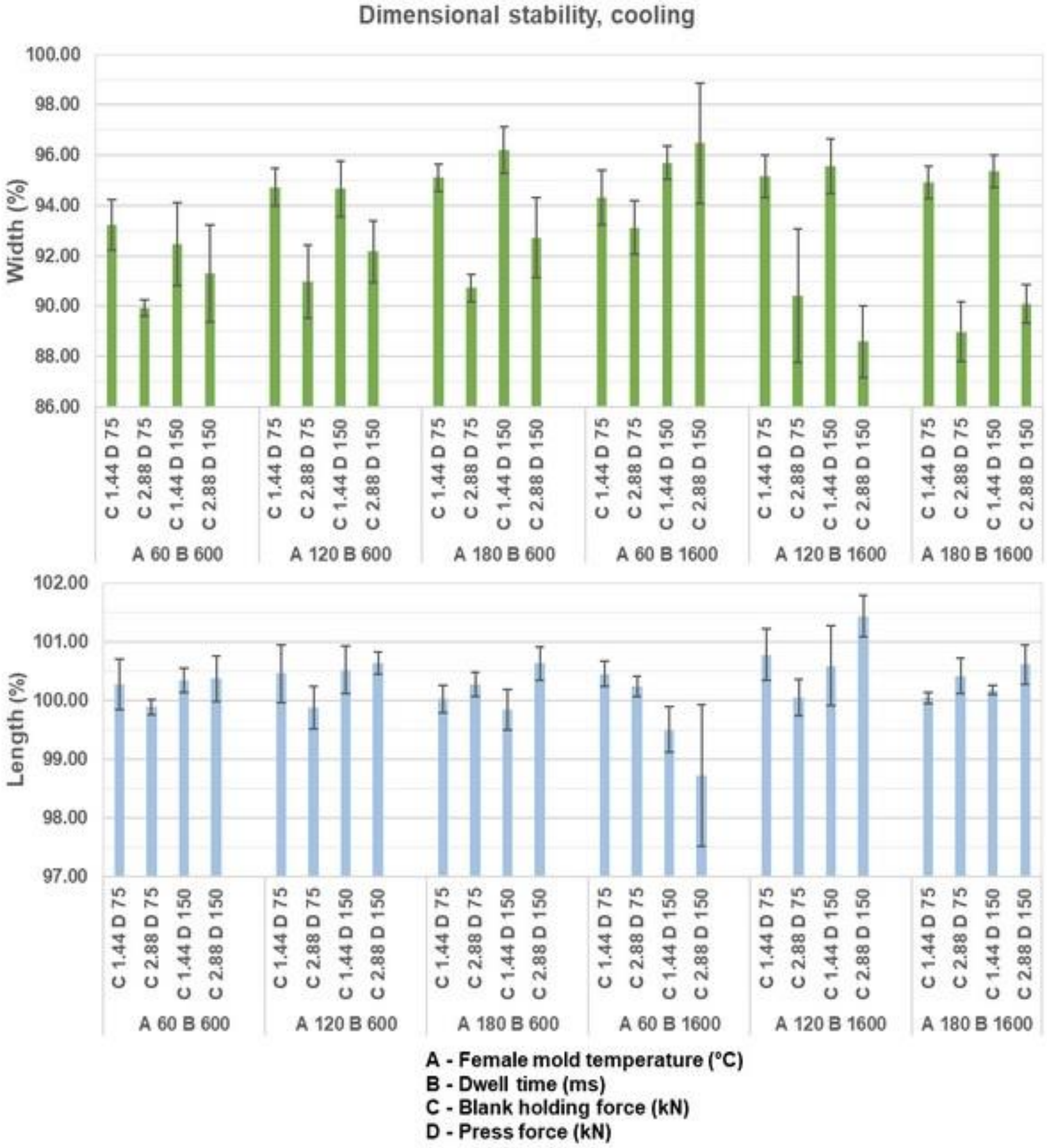

Fig. 6. Dimensional stability of trays after the cooling

The temperature of the baked oatmeal was identified as a factor affecting the temperature gradients in the paper substrates of the material baseboard. Proximity of the humid and hot mass of the oatmeal similarly affected moisture gradients of the material. The influence of baking expansion could be excluded during the cooling. Tray length changes during the cooling (Fig. 6) were visually undetectable apart from the tray corner distortion.

A cyclic change in the humidity of the environment occurred between the heating and cooling. Moisture absorption in the trays was linked to heating, and moisture desorption was linked to cooling. The cyclic humidity environment degrades paperboard stiffness (Wang and Sun 2018) and increases the material creep behavior (Considine *et al*. 1989). Temperature and moisture gradients in paperboard are linked to uneven stress concentrations and distributions in the material fibers, with gradual loss of fiber stiffness previously associated with accelerated stress relaxation in the material (Kouko *et al*. 2014).

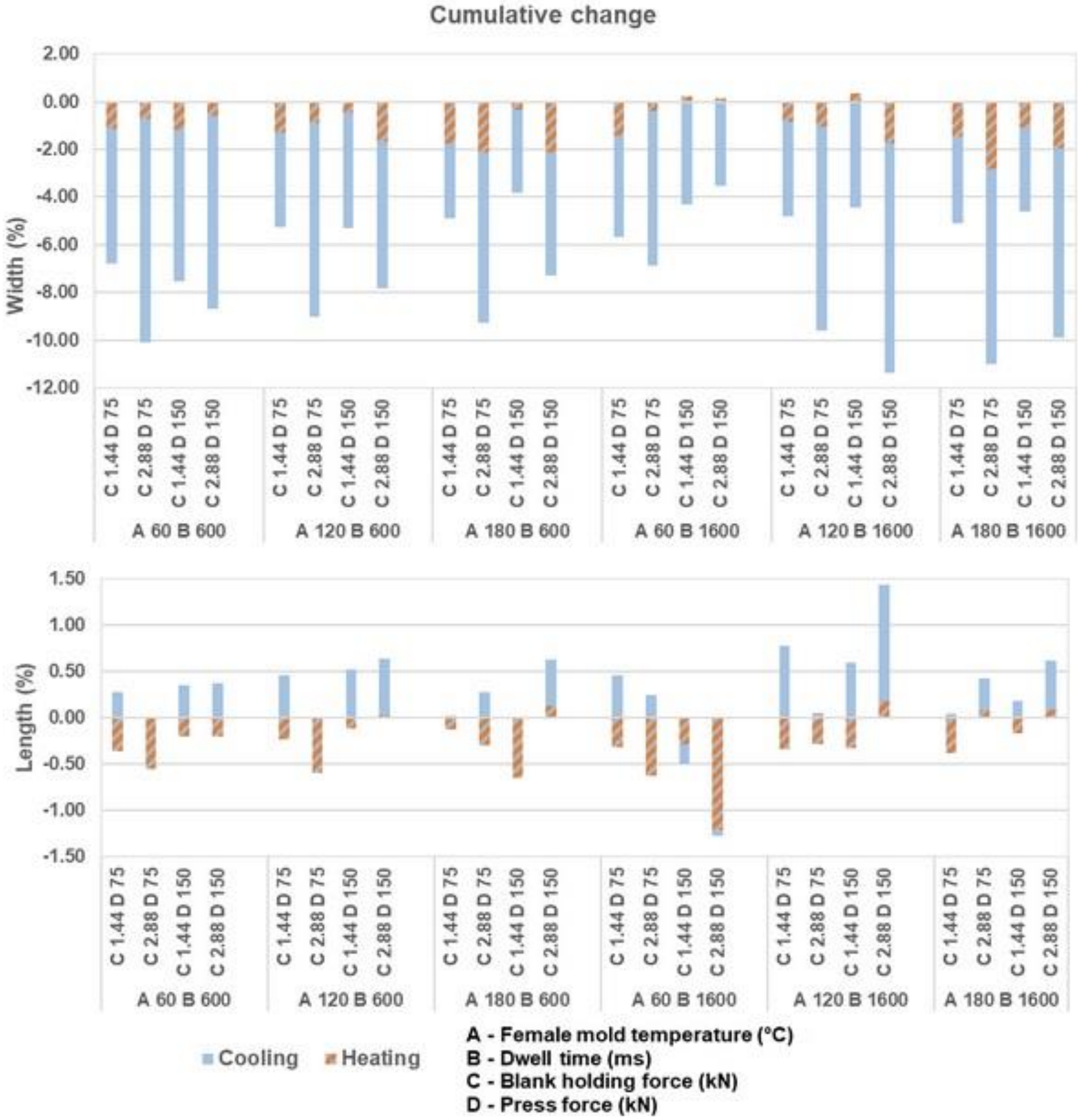

Fig. 7. Cumulative effects of the heating and cooling to dimensional changes

Successive moisture absorption-desorption cycles induce cyclic loading in the paperboard, which increases the material creep rate, as the swelling-shrinking sequence in the material fibers creates axial stresses (Guicheret-Retel *et al*. 2015). The observed distortion of the trays suggested creep, stress relaxation, and stiffness degradation in the material. The change of environmental conditions between heating and cooling was recognized as aggravating to the dimensional stability of the trays.

The tray geometry and the hygroscopic properties of the material baseboard and PET coating were viewed as factors influencing the observed mechanical response in the trays. The observed tray distortion implied uneven stress distributions and concentrations in the tray geometry, and the tray corner distortion was connected to the increased tray length changes observed during the cooling.

Optimal Press-forming Parameters

Dimensional changes occurred largely during the cooling based on the cumulative dimensional changes (Fig. 7). Among the cumulative dimensional changes, tray length decreased during the heating and increased during the cooling. The baking expansion of the oatmeal and the tray rigidity influenced the tray length changes during the heating. The baking expansion of the oatmeal and the tray rigidity showed smaller impacts on the tray width during the heating, as the material curling appeared greater in the cross direction of the material.

Sources of errors in the measurements were associated with the sample size and the handling of the trays. Errors in the heating-cooling conditions were considered minimal. A statistical analysis by means of multiple linear regression with interaction was conducted to validate the significance of the press-forming parameters to the measured dimensional changes (Fig. 8).

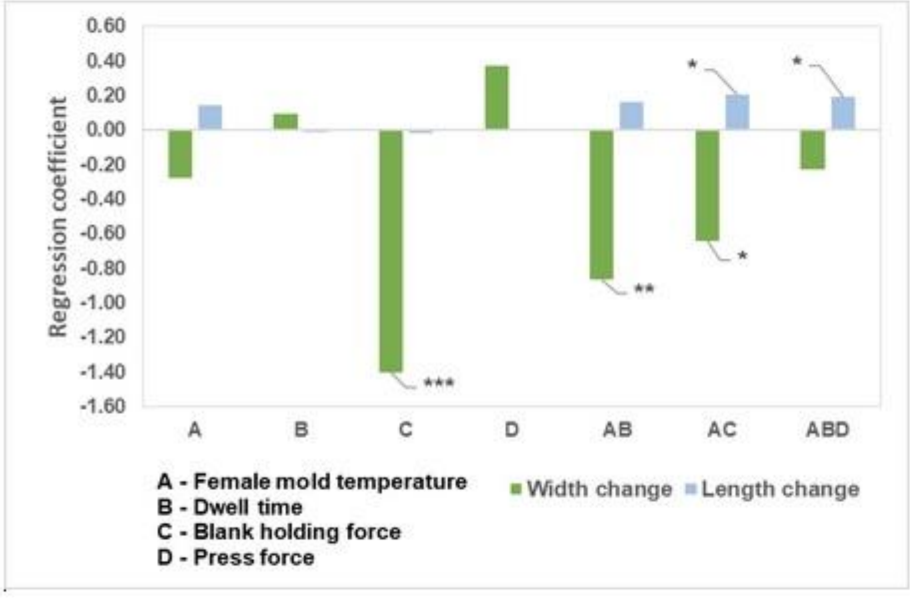

Fig. 8. Effects of press-forming parameters and their interactions to the tray width and length (significance indicated with asterisks)

The effect of blank holding force on the tray width changes was statistically significant. The pressing force and its interactions had no significant effects on the tray width changes. The combination of a 1.44-kN blank holding force, a 180-°C tool temperature, and a 600-ms dwell time was optimal in reducing the tray width changes (Fig. 9). The combination of a 150-kN pressing force, a 180 °C tool temperature, and a 600-ms dwell time was optimal in reducing the tray length changes (Fig. 10).

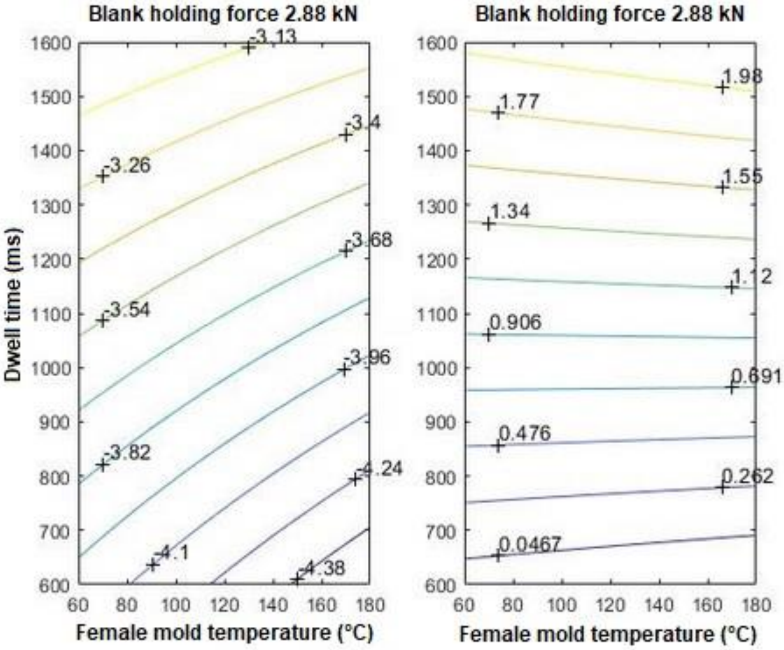

Fig. 9. Effects of tool temperature, dwell time, and blank holding force to the surface response plots of tray width change (mm) (dimensional stability indicated by the response value closest to 0)

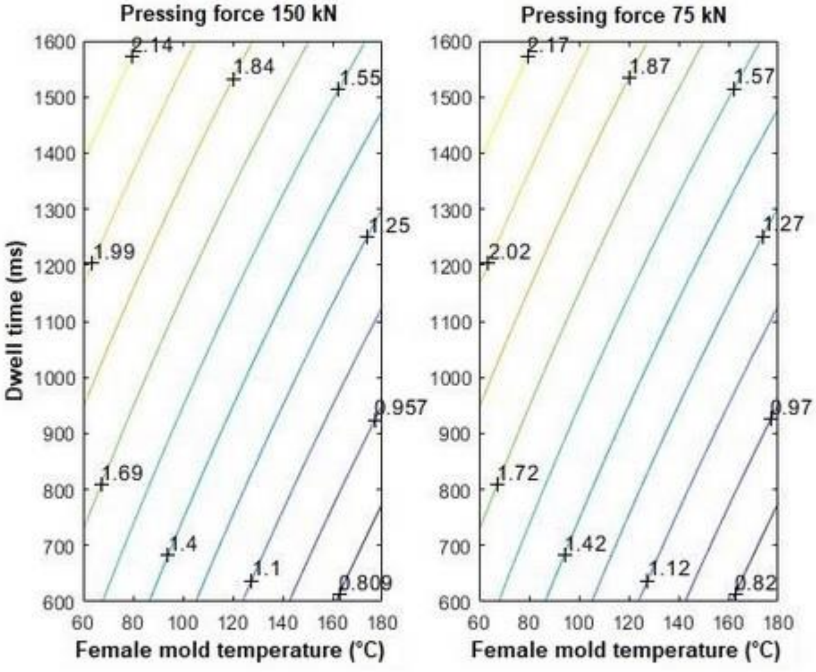

Fig. 10. Effects of tool temperature, dwell time, and pressing force to the surface response plots of tray length change (mm) (dimensional stability indicated by the response value closest to 0)

Based on the significant press-forming parameters, optimal press-forming parameters were suggested to improve the dimensional stability (Table 2).

Table 2. Optimal Press-forming Parameters

Parameter	Optimal Value	Reduced Dimensional Changes
Tool temperature	180 °C	Tray width and length
Dwell time	600 ms	Tray width and length
Blank holding force	1.44 kN	Tray width
Pressing force	150 kN	Tray length

Paperboard fibers and their bonds affect drying and consolidation of the tray geometry in its press-forming. Built-in compressive and tensile stresses of the formed geometry are derived from the forming, and the type of the material coating affects its forming behavior (Vishtal and Retulainen 2012; Franke *et al*. 2021). Temperature and tray blank moisture in forming affect drying, softening, elastic recovery, and stress relaxation of the material fibers (Vishtal and Retulainen 2012).

Higher temperatures in paperboard forming provide more accurate geometries, and higher blank holding forces increase the material stress relaxation. Reducing the influence of blank moisture in paperboard forming while improving dimensional accuracy could be achieved by shortening the drying of the material (Hauptmann and Majschak 2011). As the stress relaxation is influenced by the drying of the material, the drying during press-forming can be controlled by the dwell time and tool temperature, as the dwell time adjusts the duration of contact between the material and the heated forming tool.

The softening and drying of paperboard by increased moisture or temperature has been shown to reset plastic deformation in the formed paperboard geometry, and a higher blank holding force aggravates the plastic bending deformation on the radius of the formed geometry (Hauptmann and Majschak 2011). A larger blank holding force results in larger built-in stresses on the tray flange, which correspond with increased stress relaxation on the tray flange, as observed in the form of flange distortion.

High forming temperature has major positive effects to the stability and accuracy of paperboard geometry (Hauptmann and Majschak 2011; Wallmeier et *al.* 2016). A combination of elevated mold tool temperature and blank moisture with sufficient compression in the forming of paperboard geometries improves the bonding of the paperboard fibers. The improved material bonding is associated with the enhanced dimensional stability, as the bonded fibers are more resistant to their stretching (Hauptmann and Majschak 2016).

Compression of the moist blank reduces the distance between the material fibers, increasing contact sites for the fiber bonding. A higher thermal load from the mold tool dries the blank, enhancing hydrogen bond formation between the compressed and dried fibers (Hautpmann and Majschak 2016). The hydrogen bonds greatly affect the strength of the fiber network, and the weakening of the hydrogen bonds influences the material deformation (Groche and Huttel 2016). The moistening weakens the hydrogen bonds, yet the trays manufactured with the optimal press-forming parameters appeared more resistant to the moisture-induced material deformation.

A shorter dwell time reduces the drying of the blank and ensures elevated moisture in the formed geometry. Sufficient blank holding force and pressing force amplify paperboard compression during forming, advancing fixation and interlocking mechanisms in the bonding of the material fibers. A suitable combination of tool temperature, dwell time, blank holding force, and pressing force consequently enables fiber bonding and yields improved dimensional stability in the formed geometry.

A 180 °C tool temperature, a 600-ms dwell time, a 1.44-kN blank holding force, and a 150-kN pressing force were identified as the optimal combined parameters for improving the dimensional stability of the tested trays. Further adjustment of the blank holding force and pressing force requires compromise. Increased compression improves the bonding of the fibers in the material during forming while aggravating the stress relaxation on the flange of the formed geometry. The dimensional changes of the trays manufactured with the higher blank holding force of 2.88 kN suggested how the aggravated stress relaxation exceeded the benefits from the improved bonding of the material fibers.

Minimizing moisture content changes in the paperboard trays was viewed as desirable whenever allowed in the production of prepared food. Optimal use of the shorter dwell time can be exploited to accelerate the press-forming speed. Optimizing the press-forming parameters was validated as a viable solution for improving the dimensional stability of paperboard trays for applications requiring exposure to high RH. More research about the effects of blank holding force, pressing speed, and pressing force is needed to further optimize the use of paperboard trays in the production of prepared food.

CONCLUSIONS

1. The press-forming parameters had major impacts on the dimensional stability of paperboard trays packed with oatmeal. The trays showed reduced dimensional stability during both heating and cooling with the oatmeal. Dimensional instability of the material was more evident in the cross direction of the material fibers.
2. Dimensional measurements indicated curling of the material. The curling was visually observed in the form of distortion on the tray flange, corner, and wall on the longer side of the tray. The material response was associated with moisture sorption from the heating and cooling conditions of the experiments.
3. The oatmeal baking expansion and the sample size were identified as factors affecting the results, and statistical analysis was used to validate the optimal press-forming parameters. A 180-°C female mold tool temperature, a 600-ms dwell time, a 150-kN pressing force, and a 1.44-kN blank holding force were found to notably improve the dimensional stability. The optimal parameters can be used to enhance the functionality of the trays in manufacturing and end use.
4. The optimal press-forming parameters were linked to the improved bonding of the paperboard fibers during the press-forming. The use of a short dwell time was recommended to preserve the blank moisture and to increase the press-forming speed.

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