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Utilizing thermal imaging for non-destructive thermoformability assessment in vacuum-air pressure thermoforming of plastic-coated paperboards

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Abstract. This study addressed the limitations of traditional post-production analyses in refining thermoforming operation by employing non-destructive, real-time thermal analysis, specifically employing thermal imaging. The focus was on assessing the thermoformability of plastic-coated paperboards, a recent area of interest in manufacturing. Three paperboards underwent vacuum and air pressure thermoforming, with continuous temperature monitoring. Findings revealed correlations between the temperature distributions, the thermal profiles, and the material shape formability. Direct analysis of the thermal images enabled accurate measurement of contact areas between the mold and material. Furthermore, temperature profiles were closely related to shape profiles, particularly concerning the depth, which might be due to exothermic response of the studied materials during the induced stretching process.

Introduction

A thermoforming process stands out as a widely used manufacturing technique that allows the rapid shaping of a variety of products by using air pressure, vacuum, or mechanical force [1]. The thermoforming of fiber-based materials has recently gained increased attention as a part of the global sustainability transition. Nevertheless, thermoforming such materials presents inherent challenges due to their limited stretchability [2]. Therefore, determining the rate at which these materials can assume the desired shape has emerged as a key area of study [3].

The thermoformability of fiber-based materials has previously been assessed using a variety of approaches. These methods include evaluating depth and shape conformability through three-dimensional (3D) profile analysis, utilizing techniques such as microscopy or straightforward caliper measurements [2, 4]. Even though these post-production analyses provide valuable insights for optimizing subsequent trials, relying solely on trial-and-error methodologies may make refining optimal thermoforming parameters both complex and costly. Consequently, exploring non-destructive real-time methods that can be used in-line to provide precise insights into material performance is of great value.

Using thermal analysis, specifically thermal imaging, has long been a staple method for the real-time assessment of deformations and temperatures during the processing across a variety of material structures [5, 6, 7]. In thermoforming, thermal imaging has been used to observe temperature variations during the heating phase in order to fully understand deformations and enhance factors such as optimal thickness distributions [8, 9, 10]. Further, thermal recordings were used to determine the optimal thermoforming window for thermoplastic fiber-reinforced composites based on temperature distributions [11]. For thermoforming paperboard materials, similar thermal recordings were performed to determine the areas of contact between the material and the mold during the thermoforming process to further clarify the forming depth obtained [4].

This study aims to gain a deeper understanding of the potential utility of thermal analysis for obtaining insight into the thermoformability of plastic-coated paperboards, in particular their shape conformability. This analysis is intended to facilitate real-time optimization of the production of such materials. This objective was achieved by thermoforming three plastic-coated paperboards using vacuum and air pressure techniques, with temperature distributions being continuously recorded as the parameters of the forming process were altered. The analysis of shape conformability was approached from two perspectives: contact area and depth acquisition. A subsequent investigation sought to establish a correlation between temperature distributions, thermal profiles, and material shape conformability.

Materials

For this study, three paperboards were selected, each with a polyethylene (PE) or polyethylene terephthalate (PET) coating. *Paperboard 1* includes four alternating layers: two board layers, an internal PE layer sandwiched between the board layers, and another PE coating layer. *Paperboard 2* is a PE-coated substrate, whereas *Paperboard 3* PET-coated substrate. Paperboards with different structures and coatings were selected to determine whether the thermal analysis is affected by either the type of board material or the coating used. A prior study contains detailed information on the microscopic structures of the chosen materials [2].

Table 1 summarizes the properties of the materials studied. All materials were stored in a constant humidity chamber at 23°C and 80% relative humidity (RH) to ensure consistent experimental conditions. Measurements were conducted at a temperature of 23°C ± 1°C and a relative humidity of 50% ± 2% RH. Using an analytical balance (Kern & Sohn, Balingen, Germany), grammage measurements were conducted in accordance with ISO 536. The total grammage of the materials was determined, thereafter the substrate grammage was determined by subtracting the known grammage of plastic layer(s) from the measured total grammage of a material. The thickness of the material was measured using a digital micrometer (Messmer Büchel model 49-56, Veenendaal, Netherlands) as per ISO 534.

TABLE 1. Measured properties of materials.

Properties	Paperboard 1	Paperboard 2	Paperboard 3
Composition	PE/Paperboard/PE/Paperboard	PE/Paperboard	PET/Paperboard 474
Thickness [µm]	437	429	395
Total grammage [g/m2]	412	310.5	355
grammage of paperboard [g/m2]	357	280.5	40
grammage of plastic [g/m2]	coating layer 60 + internal layer 5	30	

Methods

The experiments were conducted on the VARIOVAC Primus thermoforming line (Zarrentin, Germany). The process involved feeding a roll of 422-mm-wide material into the machine, which was then securely clamped in the frame. Subsequently, the material was heated from the bottom until it reached a softened state. Afterward, the material was quickly moved to the forming station, where vacuum and air pressure were used to shape the material over female molds. With vacuum applied from the bottom side and air pressure applied from the top side, the materials were shaped with the stretching principle. The length of the molds was aligned with the machine direction (MD) of the materials, while the width was aligned with the cross direction (CD) of the materials. Three molds were employed on each forming step: the lateral molds shared the same geometry (Mold 1), whereas the central mold had four grooves in addition (Mold 2) (Fig. 1). Next, the formed part was moved to the cutting section of the machine for the cutting procedure.

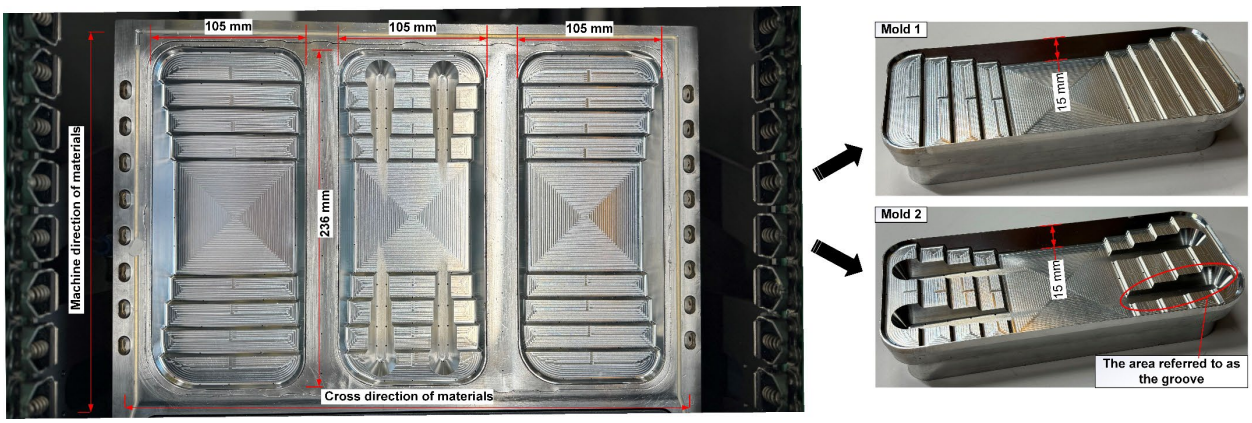


Fig 1. Molding unit used in thermoforming.

Three coated paperboards were thermoformed using a preheating/forming temperature of 110°C, a preheating/forming time of 3 seconds, and a combination of vacuum and 1 bar air pressure. In discussions, these parameters were referred to as reference values. In addition, forming parameters underwent additional adjustments for Paperboard 1, which included changing the temperature to 90°C, the time to five seconds, and the pressure to two bars. Changes in each parameter were made independently, while other parameters were maintained at their reference values. A modification of the parameters for Paperboard 1 was undertaken to determine the practicability of thermal analysis when the conditions of forming are varied. It is important to note that the selection of the parameter range was informed by a previous study performed on the same materials and using the same process [2]. Three identical samples were produced in each of the trial and the average of the results were reported.

The temperature distribution of the formed samples was captured immediately after they were released from the forming chamber using a thermal camera (FLIR A8201sc, Täby, Sweden) placed above the machine. Considering the enclosed nature of the forming chamber, it was not possible to record thermal data during the forming process. The thermal camera employed had a resolution of 1024 x 1024 and a sensitivity below 20 mK, equipped with a 25 mm lens. The spectral range of the camera is 3-5 µm. In this range of wavelengths, the emissivity values for white Paperboards 1 and 3 were 0.76, while brown Paperboard 2 had an emissivity value of 0.74. These values were determined based on previous research conducted using the same spectral range for imaging moistened machine-made coated paperboards from the coated side [12]. In this study, the thermal camera's temperature detection range was set to -10°C and 150°C. Further examination of the temperature distributions was conducted using FLIR Research's IR analysis software.

In this analysis, temperature profiles are obtained over the selected areas of interest, as depicted in Fig.2. The choice of specified lines was linked to being in the deepest parts of the shape, as achieving the required depth was identified as a challenge in thermoforming coated paperboards [2]. The line 1 corresponds to the midline of the lengthwise cross direction and represents the maximum depth change of the samples. The line 2 corresponds to the midline of the first step in the shape within Mold 2. The selection of line 2 is crucial for evaluating thermoformability in plastic-coated paperboards, as this line represents the deepest part within the most demanding section for these molds which is the groove area. Next, the photos were imported into Microsoft Visio for quantitative analysis. Following the cutting and removal of the samples from the thermoforming line, a shape conformability analysis was conducted using a 3D measurement system (Keyence VR-3200, Osaka, Japan). Using this measurement, the shape profiles were determined in the same areas of interest as the temperature profiles. By using data analysis tools in Microsoft Excel, the results of the two analyses were statistically compared.

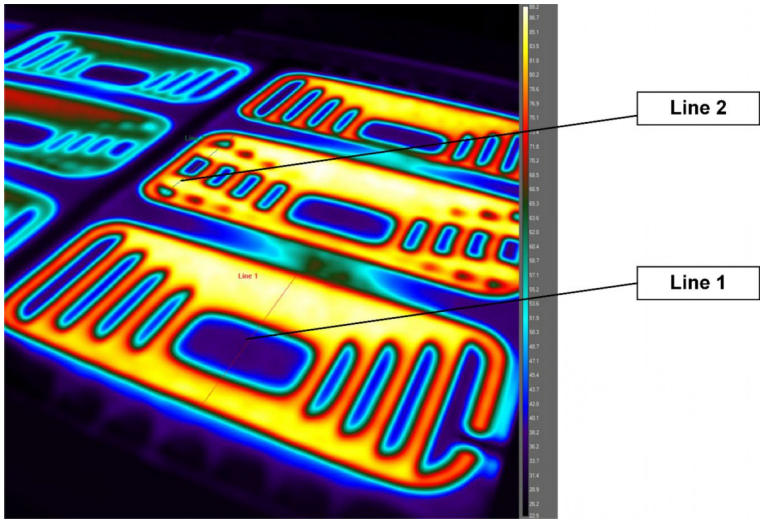


Fig 2. Regions of analysis for temperature profiles and shape profiles (the thermal image displayed pertains to Paperboard 1 formed with reference condition).

Results and Discussion

Contact Area Analysis: The thermoforming procedure involves cooling the material upon contact with the cold mold [13]. Therefore, by identifying the cold regions within temperature distributions, one can determine the zones of contact. Particularly, in paperboard materials, there is typically a curled profile if the material fails to conform to the mold and solidifies while being cooled. This methodology was previously applied to a qualitative assessment of thermoformed plastic-coated paperboards [4]. The purpose of this section is to make this comparison quantitative, with a view to estimating the accuracy of measuring the contact area by analyzing the temperature distributions that were captured.

An illustrative instance of such analysis is depicted in Fig. 3, demonstrating Paperboard 1 formed under the reference conditions. The left side of Fig. 3 illustrates the temperature distribution across mold 1 immediately after the thermoforming of Paperboard 1. The right side of depiction in Fig. 3 illustrates the corresponding measurement lines derived from shape microscopy analysis of the formed samples. In thermal image, the coldest areas or contact regions are represented by blue or dark green hues. To enhance the visualization of temperature distributions, a broader spectrum of temperatures has been selected for display. However, to detect the area of contact, the spectrum of display can be attenuate, thereby facilitating a clearer identification process. The thermal image was imported into Microsoft Visio in its original size, where the lines of contact were measured accurately.

In microscopic analysis, the x-axis represents the length of the lines, whereas the y-axis constitutes the change in depth of the lines. The variation away from zero in the y-axis is attributed to the inherent nature of thermoforming paperboard material, which tends to exhibit curvature rather than a perfectly flat line. It is important to note that, shape measurements were conducted with the samples turned upside down on a microscope to flatten curled edges, allowing for precise depth measurements. As depicted in Fig. 3, The comparison of measurements on the left and right side of Figure 3 indicates a close alignment between thermal and microscopic measurements, with some variance likely resulting from inherent measurement errors. The significance of this observation lies in its application to fine-tuning production processes, which would allow real-time adjustments to be made based on contact area measurements, even as samples are still in the production line prior to their release.

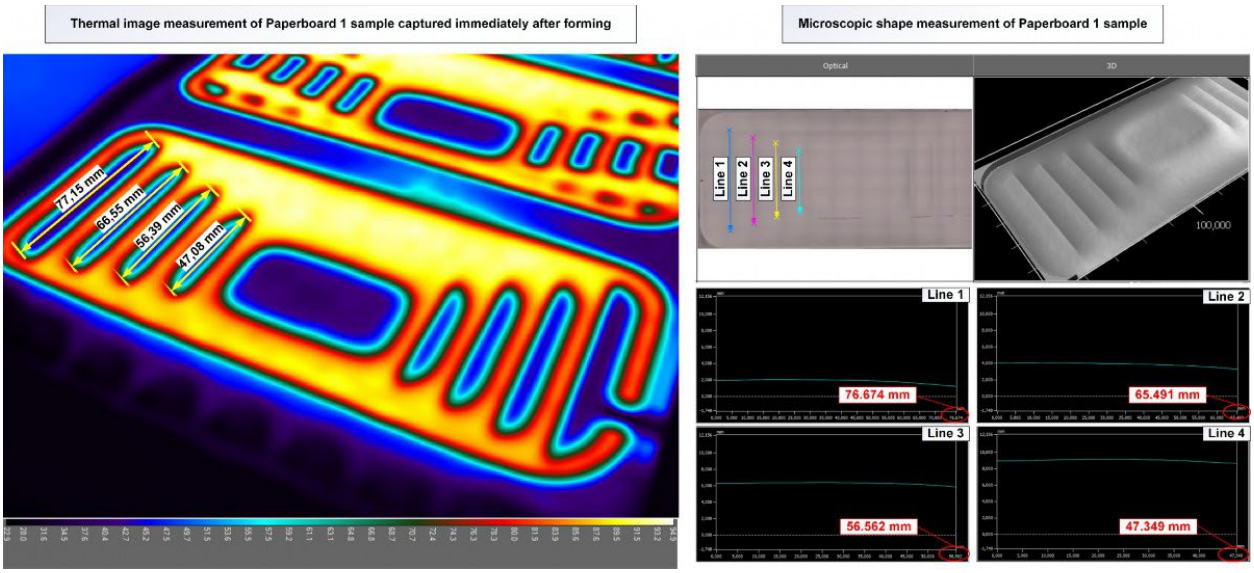


Fig 3. Conducting contact area analysis using thermal imaging and microscopic measurements.

Depth Acquirement: It is an inherent challenge in the thermoforming of plastic-coated paperboards to achieve desired depths during the forming process [4]. Real-time analysis of depth achievement can significantly contribute to the optimization of the process. This study observed a significant correlation between temperature changes in the materials and the rate at which they stretched, which correlated with their depth achievements. To elaborate on this observation, a thermal profile was first produced across the designated regions of interest (Fig. 2) to quantify the temperature change along the selected lines immediately following the release of the samples from the forming chamber. These data were then compared with the depth measurements obtained by shape the microscopy.

Fig. 4 depicts the methodology applied in this instance, illustrating the thermoforming process of Paperboard 1 under the reference forming conditions. In this specific example, the maximum temperature changes along the Line 1 (spanning from the edge to the edge) were found to be 55.6 degrees Celsius, calculated as the difference between maximum and minimum value in the thermal profile. Similarly, through shape profile analysis, the maximum depth change was determined to be 10.918 mm out of 15 mm depth of the mold.

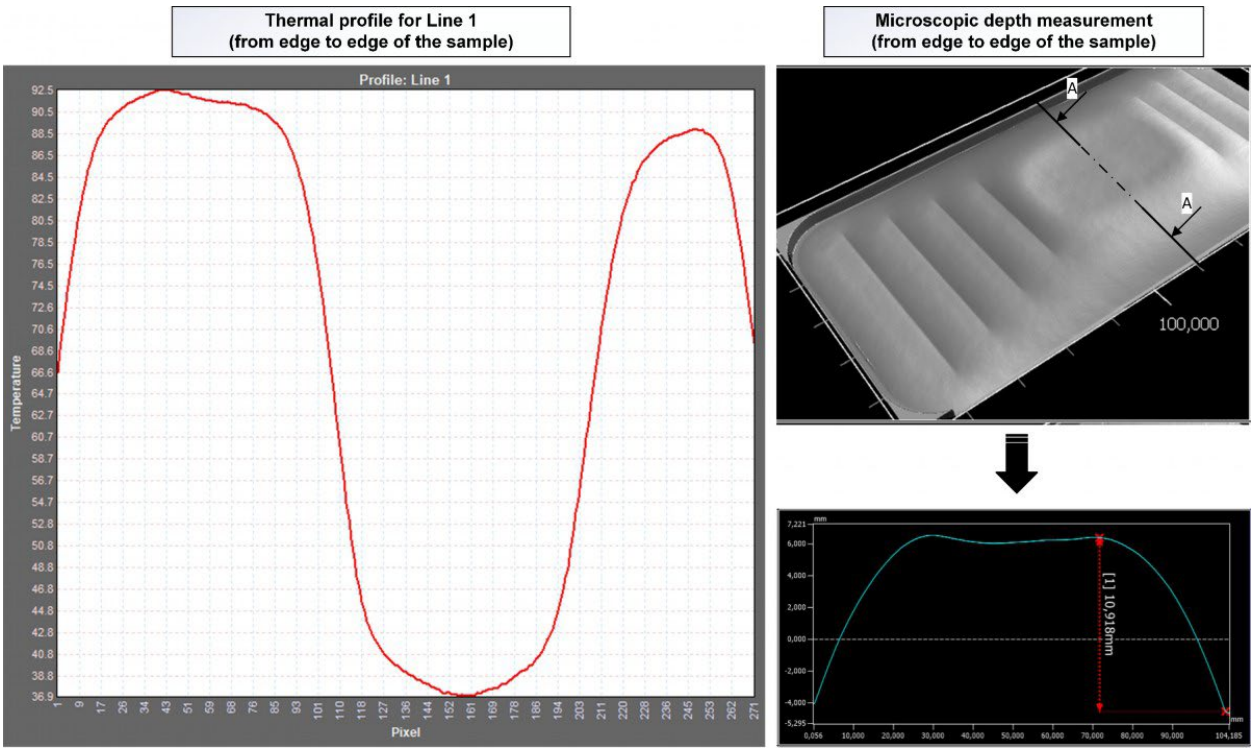
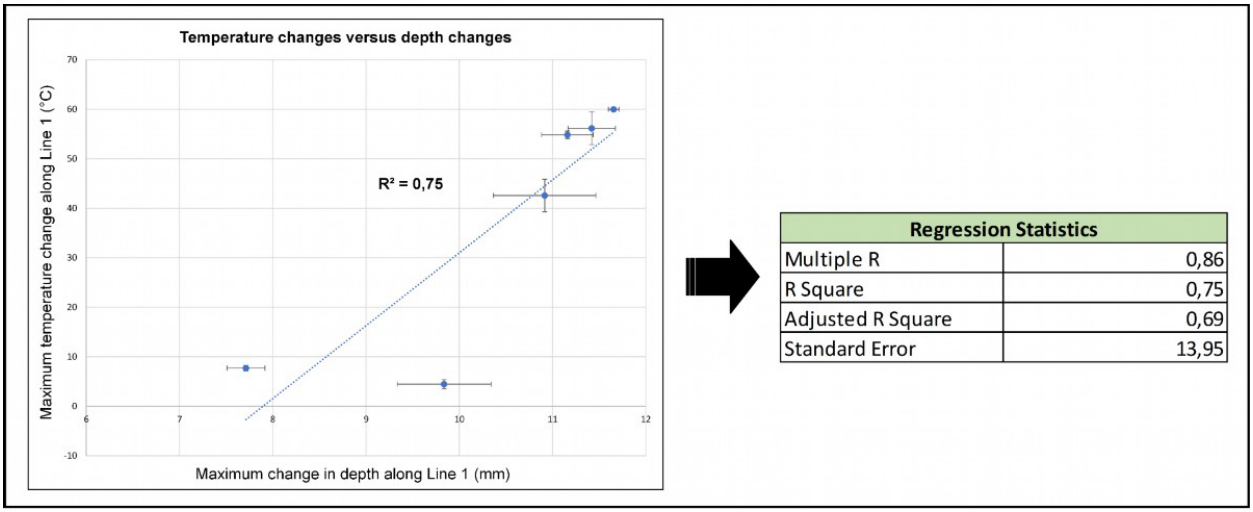


Fig 4. An example of temperature changes measurement and depth measurement for Paperboard 1.

The above-mentioned measurements had been performed for all the trials included in this study, and the data obtained was analyzed using regression statistics. As shown in Fig. 5, Observed temperature changes from the edge to edge of samples is significantly correlated with their corresponding depth changes. Indeed, the temperature changes closely reflect the rate at which the material is stretched, suggesting that a deeper shape tends to have a higher temperature difference (albeit without a complete linear tendency). This observation aligns with prior research on the stretching process of different types of materials, such as metal and fiber, where it was noted that stretching results in the release of heat, inducing a temperature change [14, 15]. Their findings elucidated that the stretching process exhibits an endothermic nature at small deformations, while transitioning to an exothermic characteristic at larger deformations.

The threshold between 'large' and 'small' deformation rates in thermoforming is challenging to define due to material behavior complexities. The assessment of deformation magnitude in this study was based on specific properties of the plastic-coated paperboards used. For instance, increasing the mold depth slightly beyond 15 mm—a depth that was used in this study—leads to material rupture. Similarly, a pressure of 2 bars, which was utilized in one trial, is at the upper limit of what the material can withstand without failure. Thus, within material's processing capabilities of this study, the used conditions might represent the boundary of large deformation for materials specific composition and characteristics. Therefore, it could cause the exothermic behavior in induced forming rate.



Regression Statistics	
Multiple R	0,86
R Square	0,75
Adjusted R Square	0,69
Standard Error	13,95

Trial	Average of Sample depth (mm)	Average of Temperature change (°C)
Paperboard 1- 90°C,3 sec, 1 bar	10,92 ± 0,55	42,57 ± 3,29
Paperboard 1- 110 °C,3 sec, 1 bar	11,16 ± 0,28	54,83 ± 0,76
Paperboard 1- 110°C,3 sec,2 bars	11,42 ± 0,25	56,13 ± 3,30
Paperboard 1- 110°C,5 sec, 1 bar	11,66 ± 0,06	59,97 ± 0,35
Paperboard 2- 110°C,3 sec, 1 bar	9,84 ± 0,5	4,47 ± 0,90
Paperboard 3- 110°C,3 sec, 1 bar	7,71 ± 0,2	7,70 ± 0,57

Fig 5. Correlation between maximum depth changes and temperature changes of studied paperboards in Line 1.

For further validation of the abovementioned correlation, the depth of the grooves was measured along the Line 2 (Fig. 2) from the shape profile, and the corresponding temperature difference was measured from the thermal profiles. A representative example of such measurement for Paperboard 1 under the reference forming conditions is shown in Fig. 6. Next, a statistical analysis of all the data points is presented in Fig. 7. The regression analysis yet revealed another strong correlation, further verifying the established relationship.

Nevertheless, from the regression coefficients displayed in Figures 5 and 7, it is evident that there is no exact linear relationship. This may be attributed to the spring-back and gradual recovery of a viscoelastic component over time, which materials like paper undergo [16]. The current shape measurements were taken on samples removed from the forming process and allowed some rest time. Due to the time gap between thermoforming and measurement, there may be a slight variation in the linear relationship between immediate temperature change after the process and depth change measured later. Notably, Line 2 shows higher regression coefficients than Line 1, possibly due to a higher rate of spring-back occurring as material contacts with mold. Analysis of temperature imaging indicates lack of contact with grooves in blue or dark green color areas; however, for Line 1 cases show material reaching bottom of mold at times. A previous study revealed contact with a cold mold being a contributing factor to spring-back in fiber-based structures [4]. Consequently, there might be a higher rate of spring-back over time in Line 1 where material contacted the mold compared to Line 2 where those not contacting the mold.

Overall, the significance of the correlations presented lies in their potential to optimize production process in real-time. Obtaining reference data that covers temperature changes, shape and depth values allows for the prediction of subsequent trials in real time. By doing so, the need for post-production analysis can be substantially reduced. It is nevertheless important to recognize that, despite the validation of this analysis focusing on depth and contact areas, other aspects of formability might still need to be examined post-production.

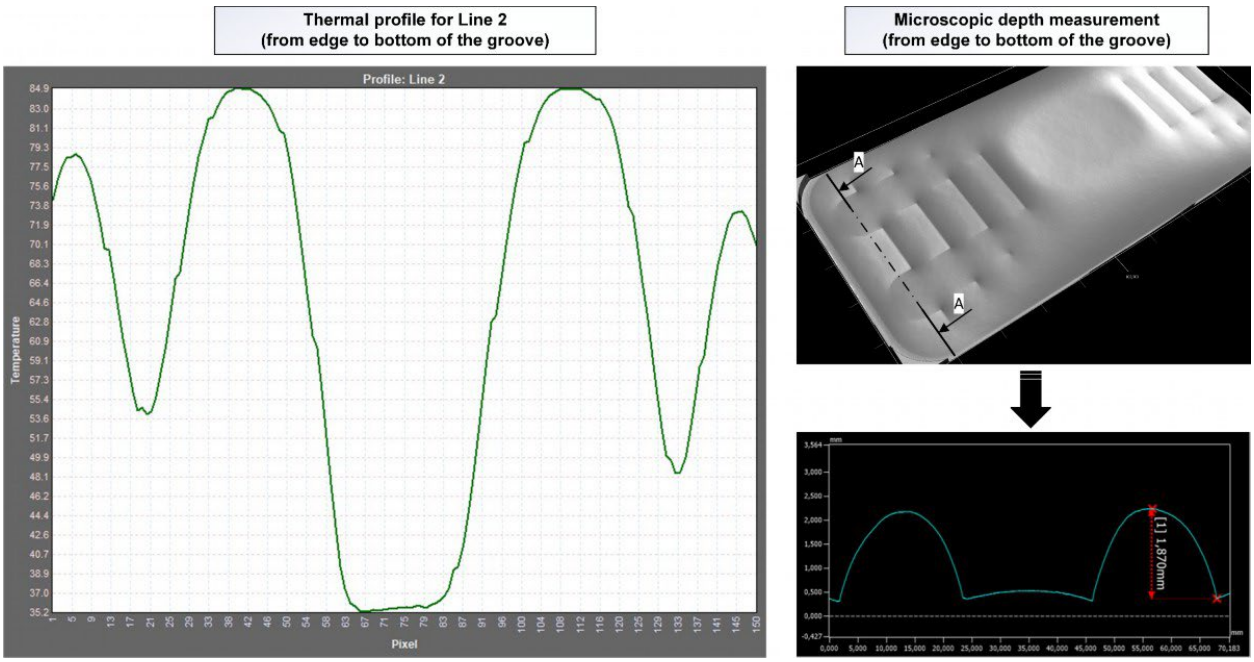
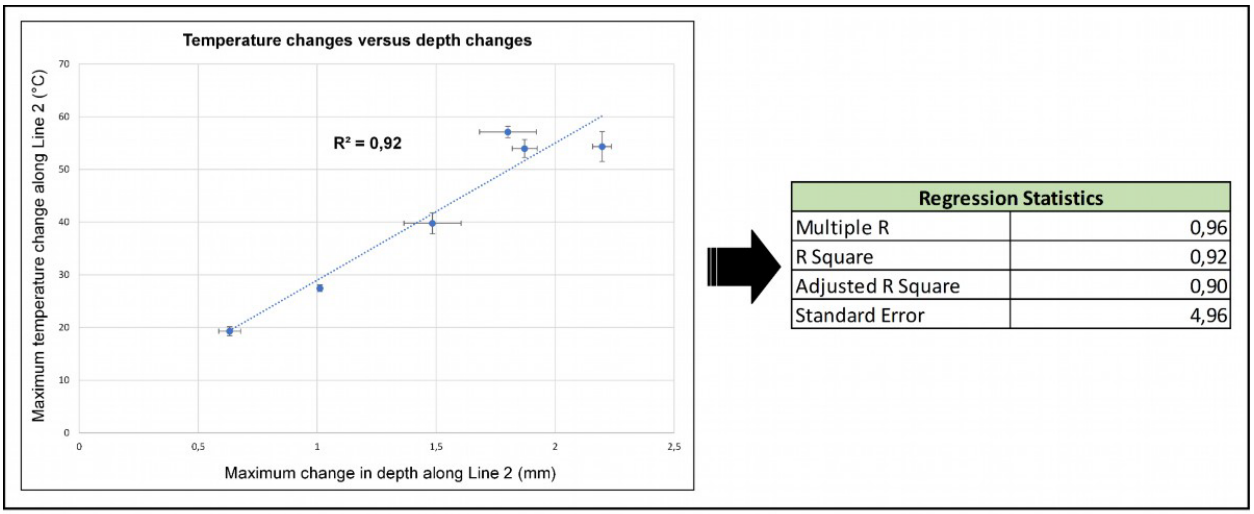


Fig 6. Correlation between depth changes and temperature changes of studied paperboards in region 2.



Regression Statistics	
Multiple R	0,96
R Square	0,92
Adjusted R Square	0,90
Standard Error	4,96

Trial	Average of groove depth (mm)	Average of Temperature change (°C)
Paperboard 1- 90°C,3 sec, 1 bar	1,48 ± 0,12	39,77 ± 2,00
Paperboard 1- 110 °C,3 sec, 1 bar	1,87 ± 0,05	53,97 ± 1,72
Paperboard 1- 110°C,3 sec,2 bars	2,20 ± 0,04	54,33 ± 2,83
Paperboard 1- 110°C,5 sec, 1 bar	1,80 ± 0,12	57,10 ± 1,06
Paperboard 2- 110°C,3 sec, 1 bar	1,01 ± 0,00	27,45 ± 0,64
Paperboard 3- 110°C,3 sec, 1 bar	0,63 ± 0,05	19,30 ± 0,85

Fig 7. Correlation between depth changes and temperature changes of studied paperboards in Line 2.

Conclusions

The purpose of this study was to investigate the potential of thermal imaging in thermoformability analysis of plastic-coated paperboards as a mean to optimize real-time production processes. For this purpose, three paperboards underwent vacuum and air pressure thermoforming, and their temperature distributions were recorded under different forming conditions. Microscopic shape profile measurements were conducted on studied paperboards to establish a relationship between

temperature distributions, thermal profiles, and shape conformability. The study indicates the following main findings:

- By analyzing thermal images directly, accurate measurements could be made of the contact areas between the mold and the material. This involved mapping the cold regions in the images that have acquired the mold temperature. This result suggest that measurements of contact areas can be conducted quantitatively using any image measurement software, eliminating the need for more complex analyses of produced samples, such as microscopic inspections.

- Regardless of the type of material or forming condition, the temperature distribution and corresponding thermal profiles of the formed samples were closely related to the shape profiles, particularly with the depth achieved. The findings revealed that temperature changes reflected the rate of material stretching, which might be due to exothermic response of the studied materials in the induced stretching process.

- The data obtained in this study can be integrated in real-time to assess thermoformability of plastic-coated paperboards and improve shape conformability by strategically selecting process parameters that yield an optimal temperature profile.

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