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Thermoforming of planar polymer optical waveguides for integrated optics in smart packaging materials

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ABSTRACT

The innovations in smart packaging will open up a wide range of opportunities in the future. This work describes the processing of additive manufactured and planar integrated polymer optical waveguides for use in smart packaging products. The previously published combination of flexographic and Aerosol Jet printing is complemented by thermoforming and thus creates three-dimensional integrated multimode waveguides with optical attenuation of 1.9 dB/cm ± 0.1 dB/cm @ 638 nm. These properties will be the basis to develop smart applications in packaging materials.

1. Introduction

Innovations in smart packaging will increase both the number and variety of possible applications. These innovations offer additional benefits that exceed the pure task of packaging. With smart packages, it will be possible to integrate diagnostic and indicator functions to provide information on the condition of the contents. Such information can concern temperature, storage time and thus indicate the freshness of the contents (Biji et al., 2015). Due to trends of increasing sensor applications, higher integration densities and electromagnetically loaded communication environments, solutions for optical communication integrated in smart packaging applications are necessary. In order to create cost efficient products, additively manufactured polymer optics will be a key enabling technology.

1.1. State-of-the-art in manufacturing polymer optical waveguides

Most common technologies for manufacturing polymer optical waveguides are based on photochemical structuring. It allows for producing high quality optical waveguides but requires complex wet chemical processes. These have disadvantages concerning throughput and being resource intensive (Tung et al., 2005). Laser direct writing is a good alternative for achieving high resolutions but has not been implemented on thin film substrates (Pätzold et al., 2017). Replication methods reach high throughputs but require cost-intensive tools like hot embossing described by Rezem et al. (2016), injection molding presented by Kalveram and Neyer (1997) and nanoimprinting. Since printing technology is suitable for low cost manufacturing and compatible to current packaging standards, it seems a promising technology. Wolfer et al. (2016) showed the printing of polymer optical waveguides at high quality.

Chen et al. (2020) compare the major printing fabrication methods for smart packaging systems and confirm the contribution to the field of smart packaging. Table 1 shows examples for devices which can be used in these systems, based on both optical and electrical sensor and communication technology. All systems are fabricated by printing technologies.

1.2. Thermoforming of functionalized substrates

There has been recent interest in research in transferring functionalized foil substrates into a three-dimensional form. By processing the material in a solid but still formable state, a previously created modification of the film substrate can be preserved. Thus thermoforming is a promising approach. During this process, strain is applied on functionalized areas which causes damage. There are active and passive methods to avoid this functional impairment. Actively, a locally resolved heating of the substrate can influence the wall thickness distribution and thus avoid excessive stretching. A matrix heating system uses this effect to create a wall thickness with uniform distribution for

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Table 1
Overview of sensor or communications technologies fabricated by printing methods applicable for smart packaging devices.

Printing method	Sensor or communication technology	Reference
Gravure printing	Transistors, solar cells	Khan et al., 2015; Krebs, 2008
Flexographic printing	Optical waveguides	Wolfer et al., 2016
Screen printing	OLEDs, solar cells	Pardo et al., 2000; Jabbour et al., 2001; Shaheen et al., 2001
Inkjet printing	Optical waveguides, graphene electronics	Bollgruen et al., 2017; Secor et al., 2013
Aerosol jet printing	Optical waveguides, transistors	Reitberger et al., 2016; Cao et al., 2017

production of resource-saving packaging and is also capable of supporting the functionalization (Bach et al., 1999). The functionality of the thermoformed component can be maintained passively by characterizing the forming behavior and considering the maximum permissible stress. This can be achieved by including the resulting distortion into the design process of the surface functionalization (Schüller et al., 2015) or by using stretchable materials (Sharif et al., 2017).

2. OPTAVER process for manufacturing polymer optical waveguides

The processing of planar integrated polymer optical systems for use in the packaging industry described in this work is based on the planar fabrication process investigated in the DFG research group OPTAVER (Hoffmann et al., 2017). This manufacturing strategy is completed in a two-step process. It allows for sufficient resolution of the structures and high optical quality surfaces.

2.1. Printing process of planar polymer optical waveguides

In the first process step, a surface functionalization by flexographic printing is performed (Fig. 1A). The material used in the printing process provides lower surface energy compared to the substrate material and thus produces modifications (conditioning lines) to allow for creating a self-assembly of the waveguide core material in optical quality applied in a downstream process (Fig. 1B).

The core material application is investigated by the use of direct printing methods like Aerosol Jet printing and dispensing technology. The most important parameter for applying the core material is the volume flow, which is changed by several gas flow adjustments concerning Aerosol Jet. This adjustment is crucial for producing high quality surfaces shown in Reitberger et al. (2017). The resulting optical waveguide core fabricated with this technology, exhibits a circular segment shaped cross-section. Fig. 2 shows an example for the quality improvement of core material application by dispensing. Fig. 2A shows the deposition without previous surface functionalization by means of conditioning lines. In this example obtains large edge waviness and reaches a height of 19.4 μm at an average width of 471 μm on the untreated Polymethyl methacrylate (PMMA) substrate.

In Fig. 2B an optical waveguide generated with the same process parameters (feed rate: v_F = 200 mm/s; volume flow: v_s = 30 μL/min; cannula diameter: d = 110 μm) on a functionalized PMMA substrate between the conditioning lines achieves a height of 43 μm at an average width of 213 μm and exhibits a contour with optical quality.

The quality of the conditioning lines directly influences the subsequent application of the waveguide core. This core is formed at the inner edges of the conditioning lines and thus adopts their shape. The quality of the conditioning lines by means of flexographic printing depends on various parameters. On the one hand, these are parameters which have to be selected before starting the printing process. This is relevant for the printing tools (printing form and anilox roller) and results in specific stamp geometries or screen width respectively. On the other hand, there are parameters which are variable during the printing process. These parameters are the printing speed as well as the feed between anilox roller and printing form (for wetting of the stamp structures) and the feed between printing form and printing substrate (for ink transfer). As reported in earlier publications (Hoffmann et al., 2017) fabricating conditioning lines with widths and distances between 100 μm and 1000 μm is achieved.

2.2. Transfer into three-dimensional integrated optical systems

In order to implement planar optical waveguides into smart packaging applications, it is required to enable the transfer into three-dimensional structures. Complementary to the forming operation, functions can be integrated to operate sensors, based on optical measurement technology. In this work, we describe the investigation by processing with thermoforming. This process step can take place at two alternative positions in the process chain (Fig. 3).

In Option 1, after conditioning by flexographic printing, Fig. 3. In Option 2, following the deposition of the waveguide core material, Fig. 3. The film substrate used in this work is a PMMA foil, which begins to flow at a glass transition temperature of approx. 105 °C and is therefore capable of thermoforming. The material used for conditioning lines as well as waveguide core material, polymerizes under UV radiation and is cured to cross-link structures. During the forming process, tension is created which causes stress in the conditioning lines and waveguide core. As result of stress, these structures tear and lose their functionality. The following section deals with the thermoforming process after printing conditioning lines, Fig. 3 (Option 2). For applying core material in a subsequent process, investigating the forming behavior of conditioning lines is necessary.

3. Results

The thickness of the PMMA substrate is 175 μm in the planar state. Depending on the degree of deformation, this wall thickness changes and thus influences the elongation occurring in the conditioning lines.

3.1. Forming behavior of conditioning lines

In the case of high degrees of deformation, an uneven wall thickness distribution occurs, which leads to tearing or distortion of the conditioning lines or waveguides respectively. Fig. 4 shows a photo of a

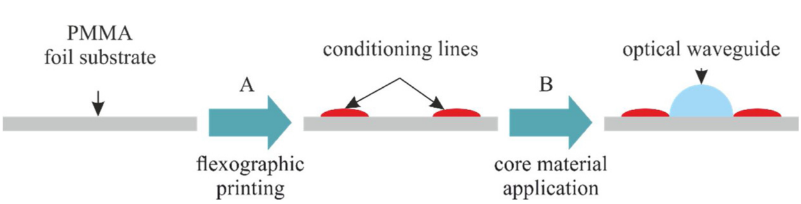

Fig. 1. Process chain for manufacturing of polymer optical waveguides.

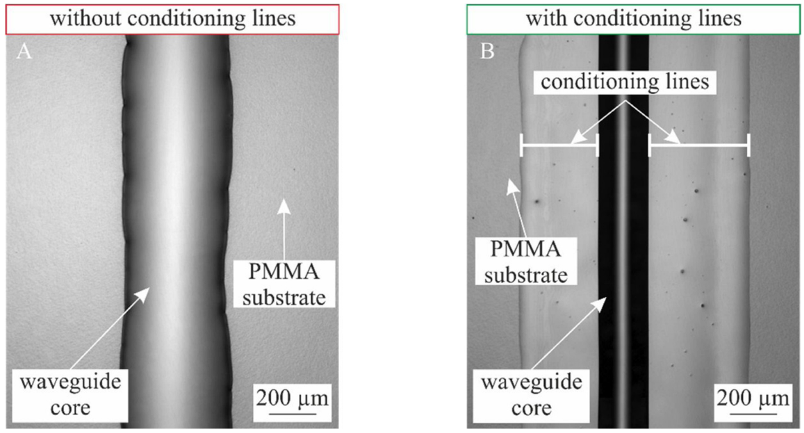

Fig. 2. Influence of the surface functionalization with conditioning lines. (A) Dispensed waveguide core on untreated PMMA substrate. (B) Dispensed waveguide core on flexographic conditioned PMMA substrate.

thermoformed functionalized PMMA-substrate with cracks. On the right side, the area with cracks in conditioning lines is displayed in more detail. The thermoforming parameters used are shown in Fig. 4.

The wetting behavior of the cracks in subsequent application of the waveguide core material by dispensing is analyzed and classified under a light microscope. Fig. 5 shows a top view on two different areas of the torn conditioning lines.

In addition to the number and location of the cracks, we identify different types of cracks. Type-1 cracks are shown in Fig. 5A, where only the structure of the conditioning line is damaged. The geometry of the waveguide core is not influenced by these cracks since their occurrence is in the volume of the conditioning lines. Fig. 5B displays type-2 cracks, where the underlying PMMA substrate is exposed and may contact the waveguide material. Due to capillary forces, this leads to wetting of the cracks and thus causes discontinuities in the edge areas of the waveguide structure. It follows that type-2 cracks prohibit the subsequent application of the waveguide core material.

In order to enable the forming process of functionalized foils for this purpose, it is necessary to determine its specific forming behavior and to include the resulting distortion into the design process.

3.2. Achievable degree of deformation

In order to determine the maximum compensable forming degree, forming tools with different characteristics are developed. Experimental investigations can detect a dependence on the geometry of the tools and the resulting wall thickness in the foil substrate.

Fig. 6 shows the basic shape of the forming tools used. They differ by a variation of the base angle "α", the height "h" and the radius "r". Depending on these parameters, we analyze forming tests on

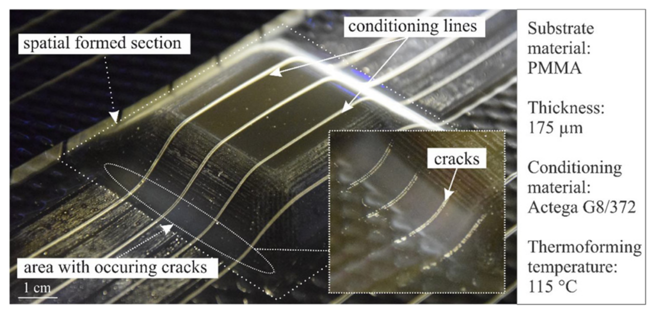

Fig. 4. Thermoformed functionalized foil substrate with occurring cracks in the conditioning lines.

conditioned foil substrates and on substrates containing finalized optical waveguides. The cracks occur primarily in the area of the negative curvature at the base of the forming tool (Fig. 6). To avoid tearing, the maximum permissible degree of deformation is determined. The relevant measure for the occurrence of cracks is the wall thickness after forming. In order to determine the achievable degree of deformation for conditioned foil substrates without occurring type-2 cracks, the wall thickness is measured. Fig. 7 (left side) shows characteristic positions along the tool surface with resulting measures. The position of maximum elongation at each tool height is marked in red.

The critical wall thickness, which ensures the formation of cracks, is determined for the conditioning material Actega G 8/372 L NVK-S. The formed conditioning lines with widths in the range of 300 µm ± 100 µm and heights of 4 µm ± 1 µm show cracks starting at a wall thickness of 165 µm ± 1 µm and thus represents the critical value. Formula (1) determines the degree of deformation:

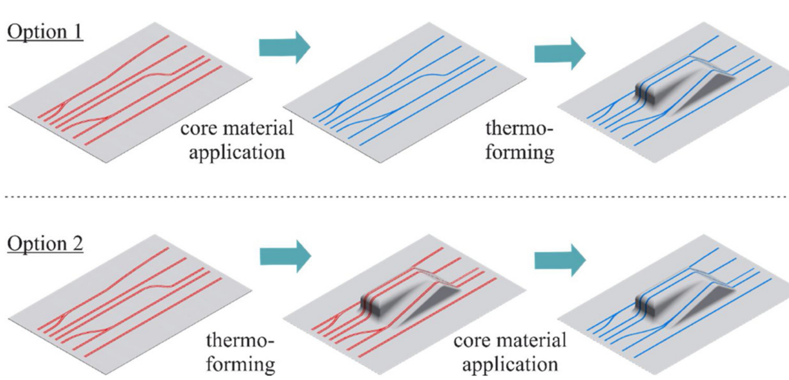

Fig. 3. Process chain for transfer into three-dimensional integrated optical system. Thermoforming following the deposition of the waveguide core material (Option 1); Thermoforming after conditioning by flexographic printing (Option 2).

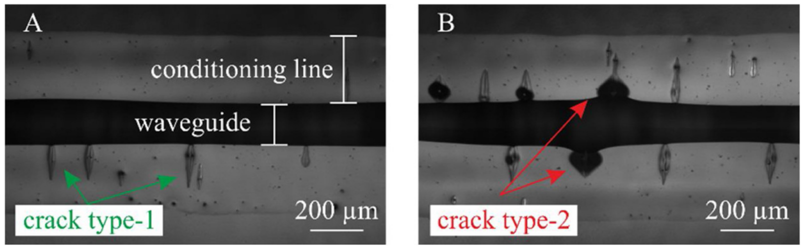

Fig. 5. Wetting behavior of different crack types in areas with high degree of deformation.

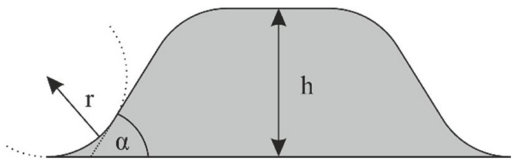

Fig. 6. Basic form of forming tools.

$$(1 - \Delta l\,/\,l_0) \cdot 100 \; = \; 5.7\,\% \qquad (1)$$

where $l_0 = 175\,\mu m$ is the film thickness of the raw material and $\Delta l = 165\,\mu m$ is the determined critical wall thickness for tearing of the conditioning lines. By using silicone additive for conditioning material (Actega G8/251 Release-050), the resulting maximum degree of deformation is extended up to 8.6%. The values determined, are used to create a characteristic diagram for tool geometries, in which a combination of tool height and base angle results in a discrete degree of deformation. Fig. 8 shows this characteristic map with the critical deformation degree as a function of the tool parameters. An integration of the characteristic map into design guidelines thus enables the production of crack-free three-dimensional foil substrates for integrated optical systems.

3.3. Resulting optical characteristics

In the case of waveguide deposition after the thermoforming process (Fig. 3 "Option 2″), not only the conditioning lines but also the actual waveguide core has to withstand an elongation. This elongation must be guaranteed without cracks in order to ensure optical transmission in the waveguide core. Nevertheless, the optical density could be modified by the induced stress in the waveguide. In order to determine the influence of the mechanical stress, one possible parameter is the optical attenuation. Thus, measurements of planar (not-transformed) and three-dimensional optical waveguides were measured with regard to this parameter.

Fig. 9(left) shows the measurement setup of the three-dimensionally thermoformed foil substrate with optical waveguides. The tools used for the forming process had radii of r = 10 mm, a height of h = 10 mm and a base angle of α_1 = 30, α_2 = 40°. For the measurement of the attenuation, a laser (@ 638 nm) was used at the end face to couple into

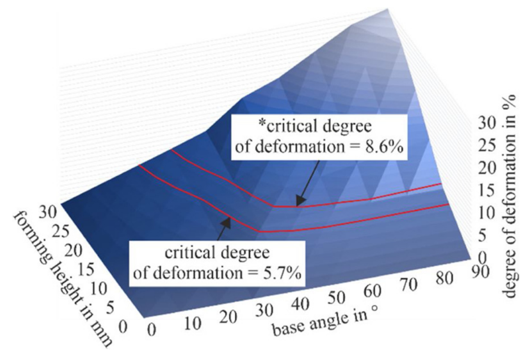

Fig. 8. Degree of deformation for conditioned PMMA foil for Actega G 8/372 L NVK-S, *Actega G8/251 Release-050.

the waveguide with a spot diameter of 36 µm at a NA of 0.1. Attenuation losses of 1.9 dB/cm ± 0.1 dB/cm without considering Fresnel losses were determined. This value is achieved for both the planar waveguides and the three-dimensionally formed waveguides. This shows that the crack-free forming of the printed optical waveguides has no effect on the attenuation losses. In Fig. 9 (right) the intensity distribution illustrates low losses due to coupling into the substrate or surrounding area as only the waveguide core is illuminated.

4. Summary

This work describes the process for fabrication of polymer optical waveguides for integrated optics in thermoformed packaging materials. The optical functionalization is provided passively by characterizing the forming behavior. The shape of the component is a frustum of pyramide at a maximum height of 10 mm. Its shape is created with printed waveguides on the surface and achieved the same optical attenuation compared to planar waveguides fabricated with the same printing process (1.9 dB/cm ± 0.1 dB/cm).

5. Conclusion and outlook

The presented results show the possibility for production of spatially formed integrated optical components by means of additive printing

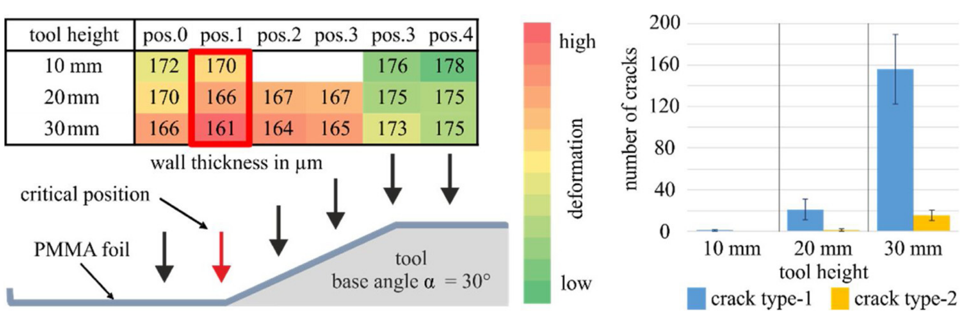

Fig. 7. *Left:* Example for the measurement of wall thickness distribution on thermoformed PMMA foil. *Right:* Number of cracks in pair of conditioning lines depending on tool height.

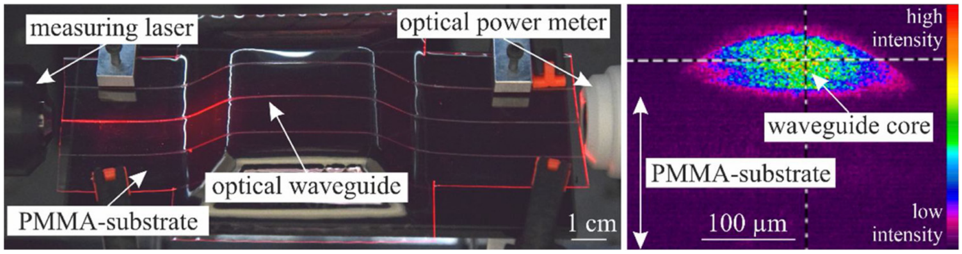

Fig. 9. Optical attenuation measurement (left) and intensity distribution (right) of thermoformed integrated optical system.

processes in combination with thermoforming. Fabrication of these optical interconnect devices allow for higher integration densities and use in electromagnetically loaded communication environments where smart packaging application is necessary. Besides the geometrical structures for conducting optical signals, it will be important to implement sensing functionalities. Opto-electronic functionalized smart packaging materials for light harvesting is already under investigation by Vicente et al. (2018) and could be expanded by using optical communication paths. In order to extend the grade of deformation for prohibiting the occurrence of cracks, laser functionalization of the printing form will be under further investigation.

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CRediT authorship contribution statement

G.-A. Hoffmann: Methodology, Validation, Formal analysis, Investigation, Writing - review & editing, Visualization. **A. Wienke:** Writing - review & editing. **T. Reitberger:** Writing - review & editing. **J. Franke:** Conceptualization, Writing - review & editing, Supervision. **S. Kaierle:** Conceptualization, Writing - review & editing, Supervision. **L. Overmeyer:** Conceptualization, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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