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Enhanced forming behavior of conditioning lines by inserted microstructures for the production of 3D waveguides

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Abstract

In today's increasingly connected world, more and more data is being produced and processed. To meet these challenges, the OPTAVER research group is conducting research on an innovative manufacturing process for 3D waveguides. In this process, so-called conditioning lines are first printed onto a PMMA substrate by means of flexographic printing. Between those the waveguide is applied by aerosol-jet in a subsequent process. To achieve a three-dimensionality, thermoforming is used. If the degree of forming is too high, the conditioning lines crack and become unusable, because waveguide material accumulation due to the cracks leads to disadvantageous optical properties such as strong scattering and high attenuation. By inserting microstructures in the flexographic printing form at points where a high degree of forming is expected, material voids occur in the printing. These microstructures act as a predetermined breaking point, leaving the critical areas of the conditioning line untouched. This can significantly increase the 3D capability, as demonstrated in forming tests.

Keywords: Ablation; Functionalization; Femtosecond Laser; Enhanced forming behavior; Thermoforming Flexographic Printing; Printing Form

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1. Introduction

Nowadays, driven by the Internet of Things (IoT) and Industry 4.0, more and more smart devices and sensors are being used. All this leads to an enormous amount of data, which is still growing exponentially [1,2]. All this data must first be fed to a data processing unit for further handling. It is often an advantage if the data line can be routed three-dimensionally. In this context, the DFG funded research group OPTAVER has developed a process for the fabrication of polymer optical waveguides [3,4]. Figure 1 shows the basic idea of this process. First, two conditioning lines with very low surface energy are applied to a flexible PMMA substrate (175 µm thickness) using flexographic printing. In a subsequent step, a waveguide is applied between these lines using aerosol jet printing (AJP). The low surface energy of the conditioning lines results in a repelling behavior, to allow for the waveguide material to flow in between these lines – a self-alignment effect. In a subsequent step, the substrate can be thermoformed into a 3D geometry. Since the aerosol jet process is a 3D-capable process, thermoforming can be performed either before or after the waveguide is inserted. Initial findings on the forming behavior have already been presented in [5]. This showed that the conditioning lines crack above a certain degree of forming and once cracked they are no longer usable. In the following section, experimental work on improving the geometry and forming behavior of the conditioning lines by laser micromachining of the flexographic printing form is explained. However, after the modification it must always be ensured that the functionality of these lines is not restricted.

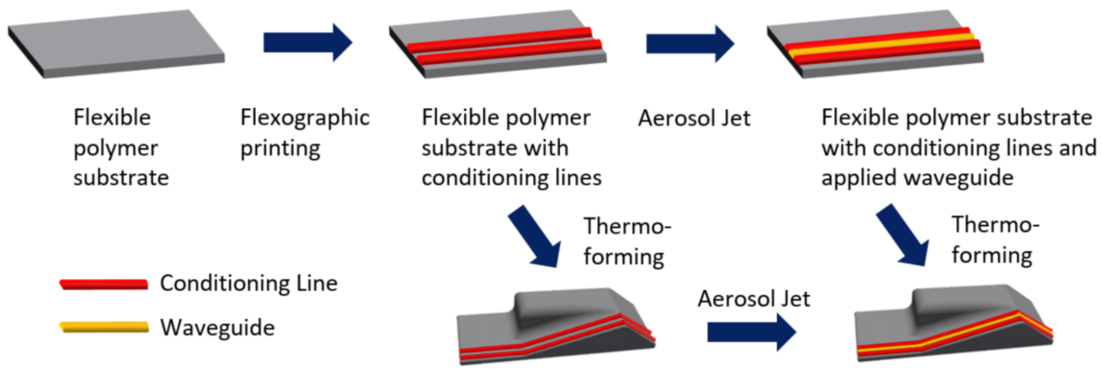

Fig. 1. OPTAVER Process chain for three-dimensional integrated optical systems.

2. Experimental

Since flexographic printing is a relief printing process, the elevated surfaces transfer the material onto the substrate. In this case the structures on the printing form which are responsible for the conditioning lines (cf. Fig. 2 (top); area a) are first modified by laser ablation in such a way that the printed lines are expected to have improved forming behavior. The stamp structure in area b (cf. Fig. 2), is expected to transfer no material. The leads to a gap in the print, where afterwards the waveguide is applied. Since the inner edge defines the geometry of the waveguide and therefore its quality, it is important that no defects and as little waviness as possible occur. Therefore, either only the outer edge or the center of the material transferring area was processed and ablated. The printing form used was a Kodak Flexcel NX, which is made of a photopolymer. The Monaco 1035 femtosecond system from Coherent was used for laser ablation. A focal diameter of 26 µm was achieved through the combination of beam expansion, galvanometer scanner and telecentric F-Theta focusing lens (f=100 mm). A total of eight different ablated geometries were investigated with regard to their formability.

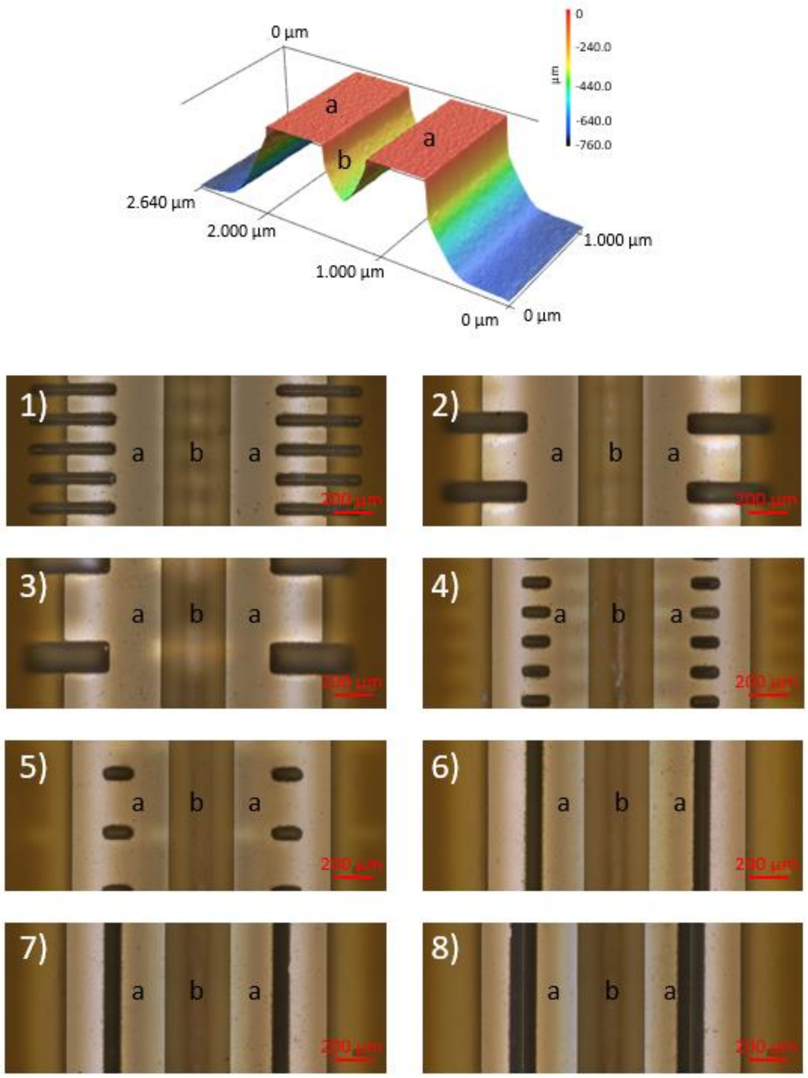

Fig. 2. Laser scanning image of a printing form (top) and images of the eight different modified material transfer surfaces (bottom). Area "a" transfers the material in the printing process. Area "b" leads to a gap in the print, where afterwards the waveguide is applied.

With these functionalized printing form, the conditioning lines were printed on a flexible PMMA substrate using a Speedmaster 52 from Heidelberger Druckmaschinen AG at a constant printing speed of 3000 sheets per hour (sph). The conditioning line material is Actega G8 from ACTEGA Terra GmbH. The substrates were then trimmed to A5 format and thermoformed using the Formech 686 manual vacuum thermoforming machine. To ensure comparability, all thermoforming parameters were kept constant. The heating power was set to the maximum, the pre-stretch function was turned off, and the mold was positioned just below the inserted substrate so that only vacuum was drawn after heating.

All thermoform tools consisted of a wave-shaped structure, as shown in Figure 3. This is composed of four identical circular segments, which exhibit a constant radius of 7.5 mm and are each tangentially connected. Due to the fact that with different angles α the inflection point takes place at different positions, the surface area could be set accurately. Since the overall height of the tool should also be kept constant, there is a base height h that compensates for height differences of the wave geometries with different angles. All tools were 3D-printed using a Form 3 from Formlabs Inc. A printed layer thickness of 25 µm ensured high shape integrity. An overview of the parameters used is shown in Table 1.

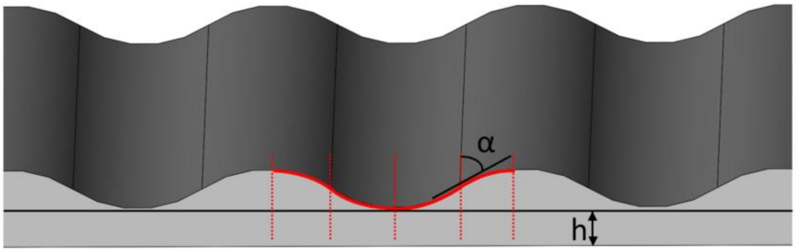

Fig. 3. Schematic representation of the thermoforming tool.

Table 1. Overview of the thermoforming tool design parameters.

Tool No.	Angle α (°)	Pre-form surface length (mm)	Post-form surface length (mm)	Magnification (%)	Wave amplitude (mm)	Height platform h (mm)
1	24.36	12.37	12.75	3.08	1.34	3.66
2	25.95	13.13	13.59	3.50	1.51	3.49
3	27.70	13.95	14.50	4.00	1.71	3.28
4	29.32	14.69	15.35	4.50	1.92	3.08
5	30.84	15.38	16.15	5.00	2.12	2.88
6	32.30	16.03	16.91	5.50	2.32	2.68
7	33.70	16.65	17.65	6.00	2.52	2.48
8	35.00	17.21	18.33	6.50	2.71	2.29

3. Results and Discussion

After thermoforming, the conditioning lines were analyzed for cracks using reflected light and laser scanning microscopy. Fig. 4 shows two laser scanning images of sections of the thermoformed substrates. The section is at the deepest point of the wave geometry (light area) and the dark areas (right and left) are the rising radii. On the left side is a cracked reference line (Fig. 4a) and on the right side is representative of an intact line with a modified pattern (cf. Fig. 2-1). Both pictures were taken at the same place with the same degree of deformation.

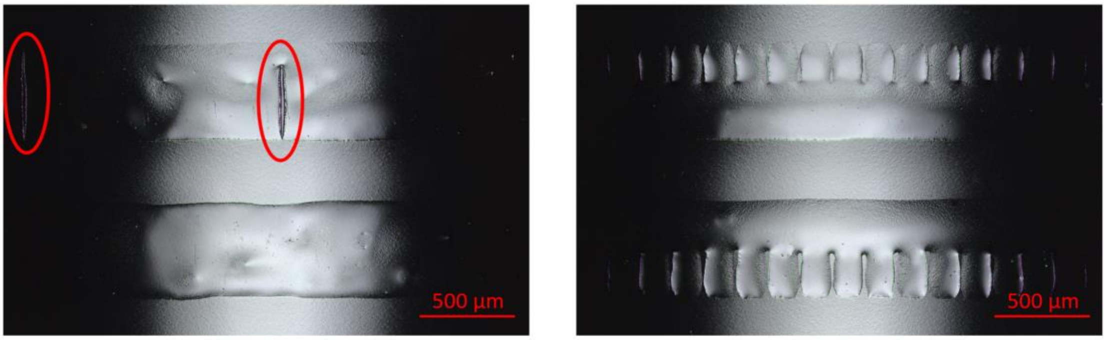

Fig. 4. Laser scanning microscope image of a cracked reference line (left) and an intact modified conditioning line (right) adapted for enhanced forming (Geometry 1).

For each thermoform tool, forming tests were carried out and subsequently analyzed to determine at which deformation rate the first cracks appear. Since the substrate does not deform linearly, the substrate thickness was further analyzed to infer the local strain. For this purpose, the thermoformed substrates were cut open and its edge was examined using a laser scanning microscope. Figure 5 shows a representative substrate thickness measurement after the deformation process using tool 8. As already mentioned, the reference thickness of the PMMA substrate is 175 µm.

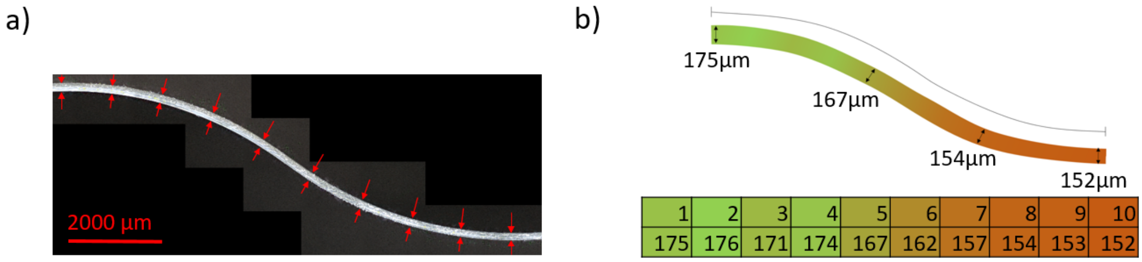

Fig. 5. Thickness deviations of the PMMA substrate due to stretching after thermoforming using thermoform tool 8.

While the substrate almost does not deform in the upper section of the wave, up to the inflection point, the maximum thinning of the substrate occurs in the bottom of the wave geometry. Normally, one would expect the first cracks to appear at the lowest thickness, i.e. at the highest surface enlargement. However, it was observed that the first cracks appear from the 6th measuring point to the bottom. This can be explained on the one hand by the fact that the thickness almost does not change any more from measuring point 8 to 10, and on the other hand the gradient with which the surface is enlarged is greatest from measuring points 5 to 8. Therefore, it is assumed that the first cracks appear where the combination of surface enlargement and its gradient are maximal. Since the thickness of the substrate changes in the last measuring points only by a few micrometers, external factors such as material inhomogeneities or printing deviations of the thermoforming tool can also be responsible for where the first cracks appear. The conditioning lines printed with a non-functionalized printing form already showed first cracks at tool 4. This corresponds to an overall surface increase of approximately 4.5% due to the waveform (cf. table 1). At the same time, the substrate thickness narrowed from 175 to approx. 160 µm. The conditioning lines with geometries 1, 2, 5, 6 and 7 showed first cracks when forming with tool no. 5. Geometries 3, 4 and 8 showed cracks with tool no. 6. However, in some tests these also remained intact. All conditioning lines then cracked latest at tool no. 7. The geometric adjustments increased the surface enlargement from 4.5% to 5.5% in some cases, which corresponds to an increase of 22.2%.

Finally, a waveguide was printed between the functionalized conditioning lines to check whether functionality was still guaranteed. This could be confirmed in the 2D case, but the waveguide application between the thermoformed conditioning lines is still pending.

4. Conclusion

In this work, different patterns were inserted into a flexographic printing form by means of laser ablation to print conditioning lines onto a flexible PMMA substrate. In subsequent thermoforming tests with a wave-shaped tool, patterns 3, 4 and 8 (cf. Fig. 2) produced the most promising forming results regarding their formability. In some cases, the formability could be increased by more than 22%. Nevertheless, the maximum formable height from wave top to wave bottom is 2.32 mm. Further experiments are expected to investigate whether the aerosol jet process is also capable to insert the waveguide between already thermoformed conditioning lines. Furthermore, the material of the conditioning lines could be further adapted to achieve a further increase in formability.

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