Inkjet printing of microlenses: A study on post-processing parameters

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Abstract

Microlenses printed by inkjet have been studied since at least two decades but are not yet implemented at the industrial scale. A lack of trust in the process accuracy is most probably the main break of microlens printing industrialization. However, inkjet process suits perfectly for microlens manufacturing. Low costs, easy implementation and versatility are the main advantages of the process. This paper tends to reduce the gap between research and industry as well as to grow the knowledge on microlens printing and functional ink for optical applications. A design of experiment as well as a model for microlens printing has been established. The study showed that it is possible to predict the exact height printed depending on drying time, drying temperature and UV curing.

Introduction

In the last few years, 3D-Printing and functional printing have drawn attention and aroused interest in the industry. Different fields of application have been investigated such as microfluidics [1], electronics [2] and optics [3] [4]. In the present work, the field of investigation is optical printing and more precisely microlens printing. Nowadays, microlenses are a key optical element. They are present in several devices for instance displays, illumination systems, sensors and cameras [5]. They are used as light homogenizers, beam shapers, or even they can increase LED efficiency [6]. Microlenses and microlens arrays are widely spread because they enable the miniaturization of the devices [7]. Light weight and low cost are therefore also aspects to take into consideration for further development [6] [8]. Despites their huge presence, microlenses require high position and shape accuracy in their manufacturing. Among the different methods of fabrication, inkjet process showed good potential. Indeed, on the graphic industry market, strengths of the inkjet process are accuracy, personalization, and low cost [8] [9]. Therefore, inkjet is a promising technology to combine industrial production, high process accuracy and versatility for microlens printing as well. Regarding personalization, for instance a large amount of individualized microlenses on large surfaces can be printed. Each microlens would have different optical properties by variating the amount of ink. As inkjet is a digital process, this ink amount variation is possible without increasing production costs. In addition, the accuracy of the inkjet process makes microlens printing possible at a reliable and reproducible position [10]. Finally, the process is based on jetting polymer which is an advantage compared to glass regarding the weight consideration.

Focusing on the fabrication itself, the most common way to print microlenses is to jet an optical polymer ink onto a pre-patterned substrate processed by photolithography [9]. The same process is used in this study. Pads were generated by photolithography. Upon these pads, the required optical polymer volumes for the microlenses are printed. The pre-patterned substrate fix the diameter of the microlens and keep the microlens at the exact required position. The ink is jetted, then it spreads on the substrate and forms the microlenses on the basis of surface tension effect and pre-patterned substrate.

The previous works on inkjet printing microlenses were mainly showing how to print and modulate microlens properties by changing the printed volume [6] [10] or the substrate properties [4] [8]. The goal in this paper is to study microlens manufacturing by inkjet printing with a focus on the post processing parameters. Therefore, the approach will highlight drying time, drying temperature and UV curing. The impact of these parameters on geometrical properties of microlenses has been studied. A fractional design of experiment was used to build a model.

Two characteristics of microlenses are controlled in order to get the required properties:

- the sag/height, which is related to the focal length of the microlens.
- the deviation of the shape from a perfect sphere, which influences the light wavefront and light propagation through the microlens.

Beyond monitoring the full process chain in order to industrialize microlens printing, the study was meant to (i) be able to control microlens geometry, (ii) optimize the post-processing parameters according to the requirements, and eventually (iii) refine the printing prediction model.

Material and method

Equipment and material

The printing was realized with a XAAR 1003 GS12U printhead in a cleanroom ISO6 - class 1000. The ink *InkOrmo 18 mPa.s* from Microresist GmbH is used in the study. InkOrmo = solvent + Ormocomp®.
The height/sag is measured by a profilometer *Form Talysurf 120 L*, Taylor Hobson Ltd.
The RMS values related to spherical shape deviation are extracted from profilometer profiles with the software *Lenslet*, Fraunhofer IOF.
The Design of experiment was made with the software *Design-Expert® Software*, from Stat-ease.

Method

The industrial chain and the method used here are defined in three steps.

- Design
- Production
- Quality control and measurements

Design

The design is the first step and the phase during which the microlens characteristics are defined for the final application. From this phase, geometrical characteristics: height, radius of curvature and microlens diameter are determined. These latter are the target characteristics named hereafter target height, target radius of curvature and microlens or pad diameter (*Fig 1Fig 1*). Then the second step is the production phase.

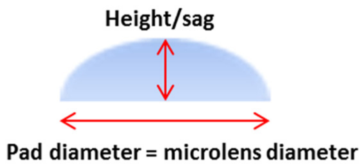

Fig 1 Microlens characteristics

Production

The production includes two different parts: substrate preparation and microlens deposition by inkjet printing. At first, the substrate preparation consists in generating pads of photoresist polymer with photolithography. The microlens will be printed on these pads (wettable area). In addition, surrounding the pads a non-wettable area is coated. Thanks to the contrast of surface energy between the two areas, the microlens will stay only on the pads at the exact required position.
Secondly, on the pads, the ink is dispensed with an inkjet printhead. The liquid ink is forming a cap sphere by a combination of spreading on the whole pad and surface tension. The pre-patterned pads enable therefore to fix the diameter of the microlens as microlens diameter = pad diameter. The ink is then jetted on the substrate aligned with the nozzles. Here InkOrmo is chosen because of its good thermal, mechanical abilities and good optical performances [10]. Because of solvent content of the ink, the microlenses are then dried on a hot plate and finally UV-cured (*Fig 2*).

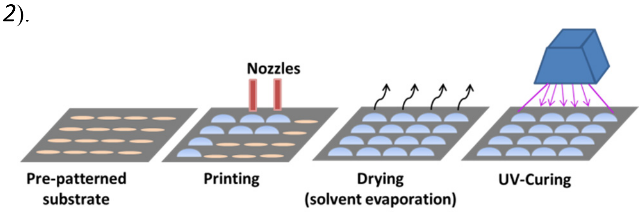

Fig 2 Printing chain process (orange = pads, blue =microlenses). The printed microlenses are obtained after the curing step.

Quality control & Measurements

After design and production, the microlenses are measured with a tactile profilometer. Furthermore, the main goals are to study how to control the microlens shape and to bring the process at an industrial scale. Accuracy, easy implementation and fast production time are key point for industrialization.

In order to collect information and understand the impact of the printing process chain on microlens geometry, a design of experiment (DOE) has been carried out. The design of experiment is a fractional DOE following a face centered central composite model. An overview of the different steps is shown in Fig.3

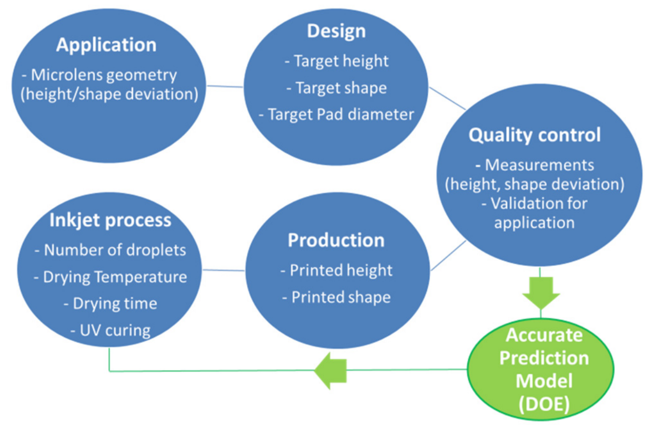

Fig.3 Microlens printing overview

Results

The DOE was made based on 30 experiments. The two output factors are height deviation (%) and shape deviation (%). A height or shape deviation of the printed microlenses could generate cross talk and transmission loss. More precisely the ***output factors*** are:

1) Height deviation (%) = $\frac{target\ height - printed\ height}{target\ height}$

The printed height is the height experimentally measured. The target height is the height from the design and the one required for the application. The printed microlens height must equal the target height in order to have the right geometry of the printed microlenses and so correct focal distance and radius of curvature. A variation of the sag height above 2% may result in a blurred image or not homogeneous light. The deviation should be therefore minimized.

2) Shape deviation = Root Mean Square (RMS) value (deviation of elliptical profile)

The shape deviation is the deviation of the microlens compared to an elliptical profile (in between a circle and a parabola). Therefore the RMS value is the average distance deviation from a perfect elliptical profile. The microlenses should not have a shape deviation higher than 50 nm. This value is set taking into consideration the wavefront error and the refractive index of the material. Indeed, a shape deviation higher than 50 nm will generate a light deviation different than the one expected for the application (projection, homogenization). In such a case, cross talks and blurred image will occur. RMS value (of elliptical profile) will directly refer to the microlens efficiency.

In order to see modification on the output factors, four ***input factors*** are studied:

- Drying Temperature (T)
- Drying time (t)
- UV power (I_{UV})
- Target height (h_t)

Firstly concerning UV curing, it is changed as followed, exposure time and UV light power varied but the total UV curing dose was kept constant (6000 mJ/cm²).
Secondly, the height is changed by varying the amount of droplets. The volume of the microlens is calculated as a cap sphere according to equation (1) where h is the target height, r the pad radius and V the target volume of the microlens.

$$V = \frac{h\pi}{6}\left(3r^2 + h^2\right) \quad (1)$$

The amount of droplets is calculated as the volume of the microlens divided by the volume of one droplet. All the volumes are calculated based only on the solid content. This amount of droplets is printed on each pad. It will be kept constant for one target height and so the volume dispensed will be the same for the printed microlenses.

The design of experiment (DOE) gave equations (Eq. 2 and 3) taking into consideration the input factors and their interactions. The input factors are as follows in the equations: drying temperature (T), drying time (t), UV intensity (I_{uv}) and target height (h_t).

$$\text{Printed height deviation} = 8.53 + 4.64\,T + 1.87\,t - 0.91\,h_t + 1.92\,T.t - 0.53\,T.h_t + 5.57\,T^2 - 3.58\,t^2 - 3.27\,h_t^2 \quad (2)$$

$$RMS = -4.36 - 0.50\,I_{UV} - 0.16\,t + 1.49\,h_t + 0.45\,(I_{UV})^2 - 0.24\,t^2 + 1.08\,h_t^2 \quad (3)$$

DOE validation:

The experiment at the center of the domain gives an average of 64.1 µm for printed height on 6 measurements and a standard deviation of s'=1.5 µm. RMS value for shape deviation at the center of the domain is 12.4 nm with a standard deviation of 3.4 nm. The RMS value shows a large standard deviation. Therefore, the RMS value and so the shape deviation will be difficult to predict and model. A printing within the experimental domain (T = 62°C, t = 8.5 h, Iuv = 100%, h_t= 70.1 µm) was made in order to validate the DOE (Table ***1***).

	DOE prediction	Meas.	Difference prediction-meas.	St dev (s')	Validation
Height dev (µm)	7.5	7.1	0.4	1.5	0.4<2.s'
RMS Value (nm)	11.9	22.5	10.6	3.4	0.4>2.s'

Table 1 Experiment for DOE validation

The experiment enables to validate the DOE for height deviation model. The coefficient of determination R^2 equals 0.8021 for the model with Eq. 2.

However regarding RMS value and so shape deviation, as expected the model is not satisfying, even by using response transformation. The model was not possible to establish however different trends appeared. The RMS value was always lower than 50nm for target heights of 29.5 µm and 70.1 µm. It was always higher for target height of 110 µm.

The model analysis will be continued in the following part only for printed height.

Based on Eq. 2, the behavior of the input factor on output factors has been determined. The results with coded values are used in order to understand the main factors influencing the microlens printing. Indeed the higher the absolute value of a factor, the higher the influence of the factor. The drying temperature has the largest influence on the height deviation. UV intensity has no impact on the height deviation.

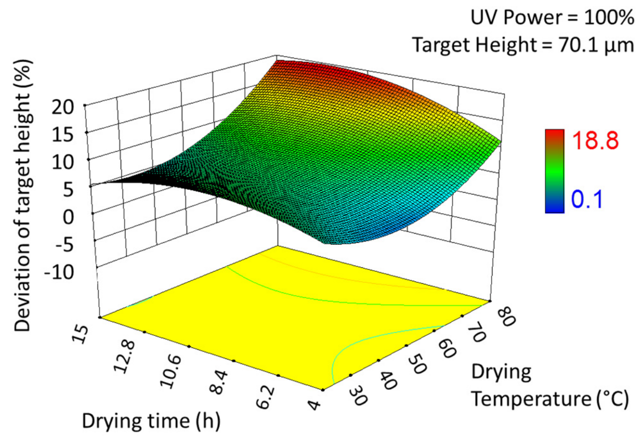

Fig.4 Variations of the actual factors: Deviation of the target height function of drying time and temperature. Target height and UV power fixed.

Then in order to get a more precise overview of the factors behavior, the variations of the printed height deviation has been studied. The actual factors and the interactions between the factors are taken into consideration in the experimental domain. Eq. 4 shows the model with actual factors, and Fig.4 the response diagram including temperature and drying time interactions.

$$\text{Printed height deviation} = -1.84 - 0.54.T + 2.t + 0.28.h_t + 0.01\,T.t - 4.4.10^{-4}.T.\,h_t + 6.19.10^{-3}.T^2 - 0.12.t^2 - 1.99.10^{-3}.h_t^2 \quad (4)$$

The equation 4 has been studied as a function. The partial derivatives were calculated to study the variations of the function "printed height deviation". The variations for printed height deviation remain as shown in Table ***2***. Starting from 20°C while increasing the temperature, the printed height deviation is decreasing. This is happening until 31°C. The minimum deviation is reached in different temperatures depending on the drying time and on the target height. Then from 44°C till 80°C, the printed height deviation is increasing while the temperature is increasing. It means that at 80°C the height deviation is higher than at 44°C, equivalent to say that the microlenses are further distant from the target when they are dried at 80°C than when they are dried at 44°C.

Factor		Printed height deviation variations			
Temperature (°C)	↗	20	31	44	80
		↘	Depends on t, h_t	↗	
Time (h)	↗	4	9.5	12.4	15
		↗	Depends on T	↘	
Target height (µm)	↗	29.5	61.1	67.7	110.6
		↗	Depends on T	↘	

Table 2 Printed height deviation variations according to input factor variations (main factors highlighted)

The same reasoning is used for drying time and target height. The printed height deviation is first increasing. Therefore the longer the microlenses are drying the further they are from target height. It reaches a maximum height deviation. The exact time when the maximum deviation is reached depends on the drying temperature. Then deviation is decreasing. It means that from 12.4 h drying time the microlenses are getting closer and closer from target height. When the microlenses are drying 15 h they are closer from the target height than when they are drying 12.4 h.

Regarding printed height, when the target height is 29.5 µm, the deviation will be 8.5% whereas for a microlens with a target height of 60 µm the deviation will be 10.1%. The maximum is reached for heights in between 61.1 and 67.7 µm, depending on the temperature. Then the deviation decreases so the printed microlenses are closer from target height when high microlenses are printed.

Discussion

Based on equation 4, Table 2 and the DOE software simulation (Fig.4), the height deviation is not always increasing or decreasing while the different input factors are increasing. In order to clarify the following discussion, a short sum-up about the ink is presented. The ink is mainly composed of solvent + Ormocomp® (polymer). The polymers are able to bond with energy input (UV light in this case) in order to form a network of polymer chains. As the network once formed cannot be formed again, the polymer is classified as duromer. The final network of polymer chains cured is what is described as the printed microlens. The target height is calculated based on the solid content i.e. the polymer content, without any solvent. When the polymer chains bond one with another to create the network, the network occupied less volume. Therefore the main height deviation is probably due to the shrinkage of the polymer during UV curing.

Back to the DOE, at first let's focus on the input factor drying time. The height deviation is first increasing and then decreasing. As the ink is composed of solvent + polymer, the first hypothesis would be that during the drying time, the solvent evaporates. Therefore it means that the less time the microlenses are drying, the more solvent remains inside the microlenses. However, the final height is calculated based on the final solid content, taking into consideration only the polymer content. Therefore if the printed height is smaller than the target height (calculated on the polymer content), the solvent amount cannot be the reason of the deviation. Indeed the microlenses should be higher than the target if some solvent was still present. The polymer has a viscosity of 2 Pa.s. So lower than 9.5 h of drying, the deviation increases because the polymer chains spread and arrange them one next to another. Once cured the probability for the functional sites to bond is higher. Thus the shrinkage rate is higher, and so the height deviation. Once the polymer chains are completely arranged, after 12.4 h, the height deviation is decreasing. The microlens will get closer from the target height. A small shrinkage is still happening. The network has a smaller volume than the polymer in its uncured state. This is why there is a slight height difference between target and printed microlenses.

Secondly focusing on the target height, if the target height increases, the deviation of the printed height increases as well. In other words, when the microlens is getting higher the deviation of the height between printed microlens and target microlens is high. It can be explained by the fact that when the target height increases, more polymer will be needed to achieve the target height. The probability that the chains bond one with another will be higher. Therefore the shrinkage will be higher and higher the difference between printed height and target height. It reaches a maximum point until when the polymer chains cannot move anymore because of steric hindrance. Furthermore the possible sites which can bond are saturated and so only few more bonding can be done. The shrinkage becomes smaller, This is why the deviation between printed height and target height decreases at a certain point.

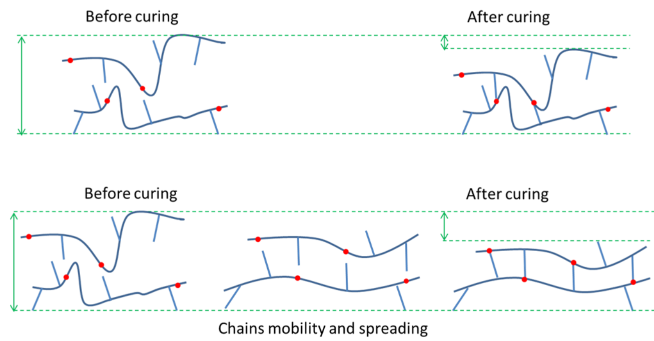

Fig.5 Scheme of basic principle of polymer chains arrangements (blue = Ormocomp, red dots = bonding sites)

The third input factor influencing the height deviation is the temperature. It is the main factor influencing the height deviation. The first reason is that the higher is the temperature, the lower is the viscosity. The polymer chains mobility increase therefore with the temperature. Below 31°C, the temperature is not high enough to make the polymer chains moving. Higher than 44°C the polymer chains starts to move one next to another to arrange them. The probability for bonding sites to meet is higher, and so the shrinkage. Therefore the height deviation increases with the temperature.

Some limits to the model should be considered. Indeed the experiments were realized on a fixed pad diameter. Furthermore, an assumption is that no microlens diameter variation is happening during the curing (verified in this study by measuring the microlens distance during profilometer measurements). Only the height is affected by the shrinkage.

Conclusion

Inkjet-printed microlenses have been intensively investigated. The study was meant to make a further step towards industrialization by monitoring and controlling post processing parameters i.e. drying temperature, drying time and UV power. A DOE was achieved and used to establish a model for height deviation prediction. The shape deviation of the microlenses could not be modeled, mainly due to the random aspect of the shrinkage. However, for heights up to 70.1 µm, the shape deviation is not critical. Finally, the model can be used in order to predict the target height and so match the printed height with the requirements of different applications. Furthermore, the drying and curing can be properly chosen and adjusted to optimize production time. The microlens printing shows encouraging results and reproducibility in order to industrialize the process.

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Sophie Sauva achieved her Master degree in printing technology at Grenoble Institute of Technology in France. She then specialised in functional printing and joined the group of Pr. Hübler, Print and Media Technology from Chemnitz University of Technology (Germany), in 2015. She investigated mainly printed solar cells. In 2016 she joined the inkjet group as scientist in Fraunhofer Institute for Applied Optics and Precision Engineering (Germany). Her topics are now focused on functional and 3D printing of Optics.