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Additive Manufacturing of Optical Components

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Abstract

Inkjet printing of 3D optical elements by using the hybrid polymer ORMOCER® is described. Focus is on a proper material formulation for providing suitable inkjet printing parameters, and on the processing of printing 3D structures layer by layer. Specific challenges for optics, like minimizing layer-to-layer interface effects for creating a close to bulk 3D structure as well as shape and roughness requirements are discussed.

Motivation

Although additive manufacturing is already an adopted technology in various fields of industrial manufacturing, the printing of optics remains to be a "holy grail" for the optical industry, since printed optical components pose several challenges to be met at the same time that are typically not present in standard additive manufactured mechanical components. In particular the demand to provide a homogeneous bulk optical material by additive manufacturing, that even for less critical illumination applications already requires high transparency without inhomogeneity, is extremely critical for additive manufacturing. This challenge comes along with requirements for shape accuracies <50 µm and a surface roughness <50 nm, for illumination optics only and orders of magnitude better for imaging optics.

Current approaches for printing optics focus on different additive manufacturing technologies such as stereolithography of polymer or glass micro-particle based resins [1, 2], or inkjet-printing of acrylate based polymeric materials [3]. A combination of inkjet printing and using a hybrid, high temperature stable optical polymer is proposed and discussed in the following.

Inkjet-printeable ORMOCER®

ORMOCER®s are hybrid polymer materials [4] that are synthesized by a sol-gel process. The process starts by creating an inorganic network through controlled hydrolysis and condensation of organically modified Si alkoxides, while co-condensation with other metal alkoxides (Ti, Zr, Al alkoxides) is also possible. In a following step the polymerizable groups that are fixed to the inorganic network react with each other in a thermal and/ or UV-initiated process, synthesizing an inorganic-organic copolymer.

ORMOCER® exhibits excellent mechanical, thermal and optical properties: refractive index n @ 635 nm 1.44-1.59, optical loss <0.1 dB/cm @ 633 nm - <0.55 dB/cm @ 1550 nm, degradation temperature >400 °C, short term temperature stability >270 °C/> 1min. Although it has a high viscosity, ORMOCER® has already been formulated in an inkjet suitable composition by company micro-resist GmbH [5], using specific solvents that take up to 70% of the printed volume. The disadvantage of the high solvent content is that it requires a thermal evaporation after printing and before UV-polymerization, prolonging the process time and affecting achievable shape accuary.

Based on these findings an alternative ORMOCER® formulation was derived that is based on reactive solvents that remain in the ORMOCER® matrix. A reactive solvent used was DDDMA (1,12 Dodecandiol dimethacrylate 95%) with a volume content of up to 66%. Fig. 1 shows the transmission for the ORMOCER® version Ormocomp in pure vs. the solvent (InkOrmo) and the reactive solvent (Ormocomp + DDDMA) formulations, fig. 2 plots the dispersion of the reactive solvent formulated ORMOCER®.

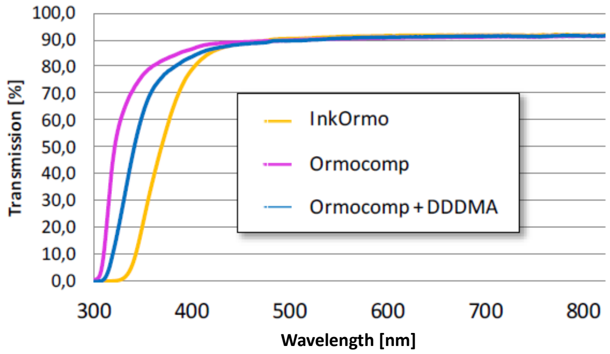

***Figure 1.** Transmission of the reactive solvent formulated ORMOCER®*

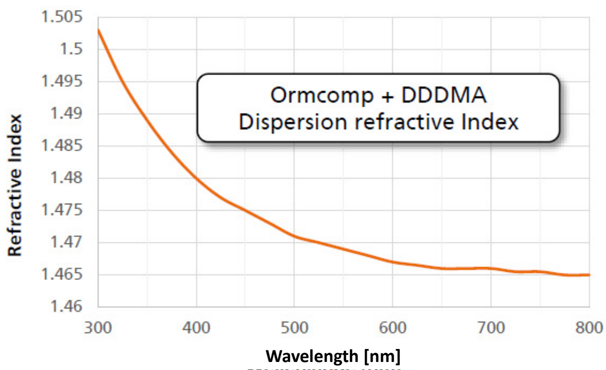

***Figure 2.** Dispersion of the reactive solvent formulated ORMOCER®*

Inkjet-Printing Process Optimization

Printing was carried out using standard industrial printheads from suppliers XAAR (XAAR 1003) and Konica Minolta (K-M 512L). Both are based on a piezoelectric mechanism, shared wall – shear mode, using standard 360 dpi. After the 3D design has been sliced to obtain geometry data for the individual layers, the printing is done layer by layer, following a printing-curing scheme. A layer is printed and then UV-cured @ ca. 400 nm, this scheme is repeated up to several thousands of times in order to get 3D structures (fig. 3).

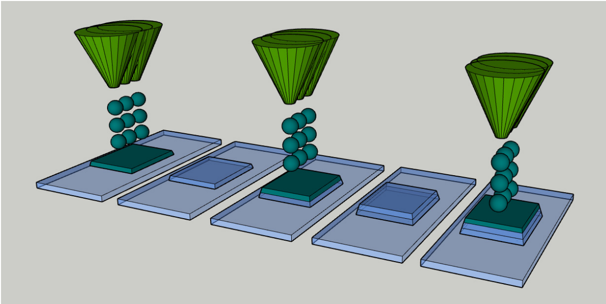

Figure 3. *Layer by layer printing of optical bulk structures*

The challenge for this process scheme is first to optimize each layer geometry to pre-compensate for errors that might accumulate during the printing of all layers, and second to tune the UV-curing of each layer in order to provide both mechanical stability for further layer printing on top of it as well as remaining reactivity to form an interface with the sub-sequentially printed layer. Thus a design-of-experiment para-meter variation was conducted, using an UV-LED based aerial illumination @ 395 nm and varying UV doses as well as illumination times. The optimum parameter combination was derived measuring direct transmission and absorption in the wavelength range >400 nm, according to ISO as the desirable function 13468. Fig. 4 shows the finally obtained performance, indicating that a transmission of ca. 88.5 % and a loss (absor-ption and scattering) of ca. 5% @450 nm have been achieved.

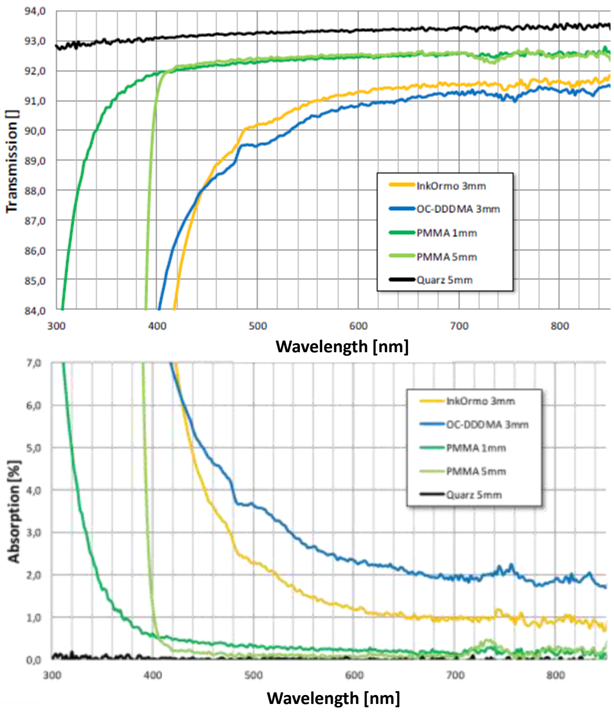

Fig. 4. *Transmission and absorption of an optimized, layer by layer printed Ormocomp+DDDMA bulk structure (compared with InkOrmo, standard PMMA and fused silica)*

Demonstration Showcases

In order to study inkjet printing of optical 3D structures, several showcases have been defined that allow for the characterization of optical properties. The showcases are a plan-parallel (transmission and losses, surface shape accuracy and roughness), a pyramidal structure (transmission, shape accuracy and roughness), and a freeform (transmission, surface roughness and shape deviation). All showcases have been printed using the layer-by-layer approach, the OrmoComp+ DDDMA material formulation, and an optimized process regime according to the finding of the Design-of-Experiment parameterization optimization.

Plane-parallel Plates

Plane-parallel plates (Fig. 5) with dimensions of 20x20x1-3 mm^3 were used to optimize the layer-by-layer printing and to characterize transmission as well as surface roughness and shape deviation. A shape accuracy of 20 µm P-V and a surface roughness R_q ca. 50 nm was measured on the top surface of the plates.

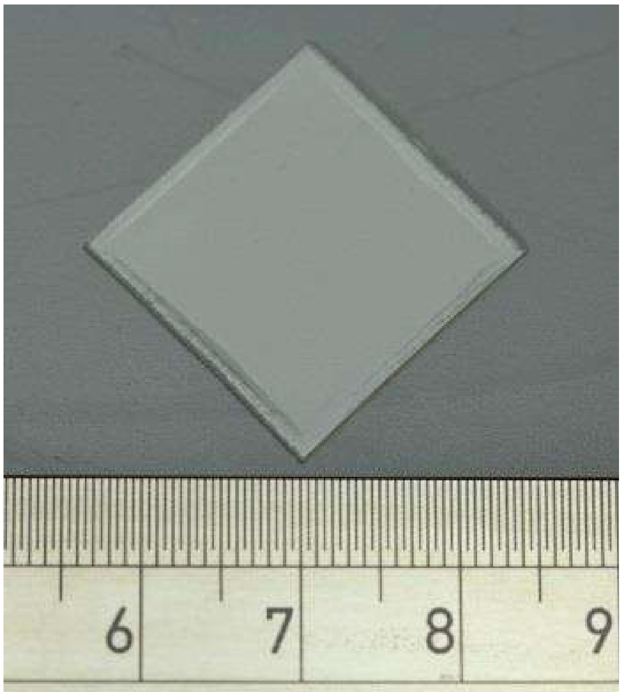

Fig. 5. *Inkjet printed plane-parallel plate*

As the plane-parallel plates were used for transmission and absorption measurements, for comparison also the standard optical materials PMMA (polymer) and Fused Silica (glass) were procured for different substrate thicknesses and measured in order to compare performances of the OrmoComp formulation in the spectra. It was shown that above 400 nm wavelength the thickness of neither OrmoComp+DDMA, PMMA nor Fused Silica has any impact. Below 400 nm thin layers show better transmission, better reflexion and less losses (less scattering and less absorption). In average in the visible spectra (400-800 nm) OrmoComp shows a transmission of 90.1%, PMMA 91.8%, and Fused Silica 93,3%. Fused Silica shows a better homogeneity for all wavelengths. OrmoComp shows better transparency and less loss than PMMA for wavelength under 400 nm, but in the visible spectra 400-800 nm, the transmission of Ormocomp is 1.7% lower than PMMA and 3.2% lower than Fused Silica.

The plane-parallel plate revealed that the wavelength range between 400 nm and 450 nm is critical for the thickness dependent transmission, due to the photo-initiators that are required for the UV-curing process. Fig. 6 shows that the transmission drops dramatically for the wavelength of 400 nm, already at a thickness of 3 mm of the plane-parallel plate. At the moment investigations are carried out that quantify the influence of different photo-initiators onto the transmission performance.

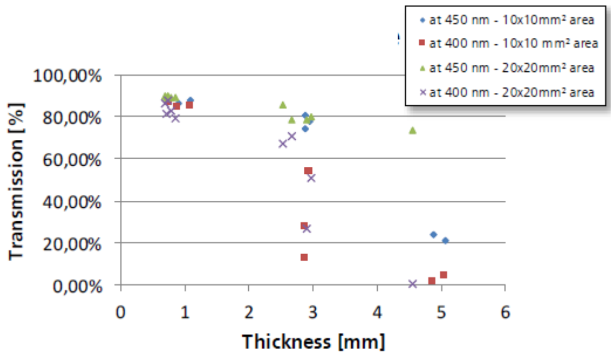

***Fig. 6.** Thickness dependent transmission @400 nm and @450 nm*

3D pyramidal structure

For a geometrical shape characterization pyramidal structures were used in order to demonstrate the accuracy of the inkjet printing process in the 3D bulk structure manufacturing. The pyramidal structures were defined to have dimensions of 10x10x5 mm3 (LxWxH) and a side wall angle of 85°.

***Fig. 7.** 3D pyramidal structures, layer by layer inkjet printed*

The four side wall angles of 27 pyramids were measured to be 85° in average, the minimum angle was 81°, the maximum angle was 88°, and standard deviation was 1°. Considering these results 85°±1° for 95% of the measurements, the inkjet process can achieve a high reliability regarding angles of a given structure.

Using a standard resolution of 360 dpi, in the printing direction the deviation in length was in average +190±140 µm, while for perpendicular to the printing direction the length was in average +10±100 µm. Thus in the printing direction the length was determined to be less accurate. This is due to the print-head movement that generates inaccuracy in the drop deposition and thus in the dimensions. It results in a higher length and a higher deviation compared to perpendicular to printing direction. Nevertheless, it can be concluded that inkjet printing can produce accurate object including high design flexibility with reproducibility of ±100- ±200 µm.

The P-V shape accuracy on the top surface was again measured to be ca. 20 µm, having the same roughness as the parallel plate. Nevertheless it has to be mentioned that the sidewalls exhibit a strong and visually observable roughness, which is a typical issue in additive manufacturing. Finally printing a smoothing layer onto the sidewall enabled to significantly reduce this sidewall roughness effect.

3D freeform structure

A freeform (ca. 50 mm in diameter, maximum structure height ca. 1 mm) was printed and a CT scanning was performed with a resolution of 33 µm. The measurement accuracy is 15 µm. The freeform was printed based on a CAD model. The CT imaging gives an overview of the deviation between the model and the printed sample. Fig. 8 shows that the printed freeform deviates from the CAD model in most of the parts in the range of <±300 µm. Positive shape deviation in the center parts and negative deviations in some outer parts are probably due to ink flow during printing and before UV-curing, another source of deviation is again shrinkage during UV-curing. However, 70% percent of the geometry is in the interval deviation ± 300 µm. The freeform design was made to provide patterned refractive light re-direction in the far field for a collimated beam, to be used e.g. in individual logo projections.

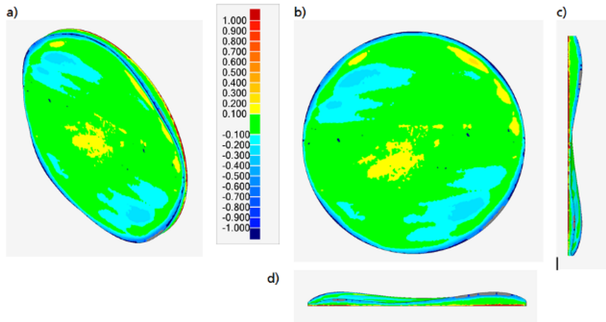

***Fig. 8.** Freeform CT imaging (a) overview, b) top view, c) and d) profile views), shape deviation is color coded in millimeters*

Conclusion

Using a modified ORMOCER® formulation inkjet printing of 3D bulk polymer-optical components has been demonstrated. Due to the hybrid anorganic-organic composition of ORMOCER® such components will provide superior properties over standard acrylate based printed components in special application environments such as medical or automotive, while making use of the additive manufacturing process and thus enabling for a complete new way of manufacturing individualized optics and no tooling costs. Without process optimizations transmissions in the range of ca. 90% have been proven as well as shape accuracies in the range of ±100 µm, which already come close to the requirements of e.g. LED illumination optics.

Next to the printing of pure bulk optical components embedding of further functionality by either printing or by hybrid integration is considered to be a future route for the manufacturing of multi-functional optical components that cannot be produced by any standard optical manufacturing technology.

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Author Biography

Erik Beckert received his Dipl-Ing. degree in precision mechanical engineering (1997) and his PhD in mechanical engineering (2005) from Ilmenau Technical University, Germany. Since 2001 he is working at Fraunhofer Institute for Applied Optics and Precision Engineering (IOF), where his work has focused on the micro assembly and system integration for miniaturized optical and opto-electronical systems.

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