Potentials and Challenges in Additive Manufacturing of Nanoparticle-infused Silicone Optics

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Extrusion-based silicone manufacturing processes enable the fabrication of functionalized optics by controlling the material properties of each printed voxel. In this paper, potentials of functionalization as well as challenges in the manufacturing of highly transparent silicone via Freeform-Reversible-Embedding are presented.

1 Introduction

Highly transparent silicones for optical applications are UV resistant materials with hyperelastic behavior. They come in a high-viscous liquid state and become solid elastomers after curing. By controlling the material properties of each volume pixel (voxel) of an optical component, a high degree of functionalization freedom emerges. This can be realized either by a local variation of the mixing ratio of two-component silicones [1] in order to realize a so-called GRIN-optic or by a voxel-wise addition of another material during the manufacturing process. By using materials which are externally addressable e.g. by applying a magnetic field, the properties of the optical element can be manipulated.
Additive manufacturing through Freeform-Reversible-Embedding (FRE) [2] provides the required design freedom for these approaches. Since we focus on the second idea, different nanoparticles as additional materials are considered. Due to their small size they can be handled easily within the FRE process. The mixing ratio of the standard silicone and that infused with nanoparticles can be chosen freely in the manufacturing process. Both silicones are blended before they reach the common extrusion nozzle.
In the following the potential of silicone optics with fluorescent, ferromagnetic and shape memory nanoparticles is explained using design examples. While fluorescent materials change the energy level and direction of transmitted photons, ferromagnetic and shape memory particles can be used to manipulate the shape and therefore e.g. the refractive power of the optical element.

2 Functionalizing potentials for silicone optics

Fluorescent particles change the energy level and thus the wavelength of incident light. Hereby, radiation of high energy such as UV is absorbed by the particles and converted into radiation of lower energy, e.g. in the visible range. Thus, optical components fabricated with a particle-silicone mixture gain emitter functions. When applied as a filter in front of a sensor, incident wavelengths can be shifted towards regions of higher sensitivity of the detector. Especially for the detection of UV radiation, silicone is well-suited as host matrix for the conversion material due to its high transparency for and resistance against UV radiation. Possible applications are solar concentrators with increased efficiency [3] or waveguide-based sensors for UV radiation. In the second example the waveguide with fluorescent particles can be manufactured without any incoupling structures. While the excitation light is not coupled into the waveguide in a significant way the reemission shows another directivity so that a portion of this radiation is guided to the detector.

With ferromagnetic particles the silicone's elasticity can be addressed. By applying an external magnetic field the shape of the silicone body can be changed. As shown in Fig. 1 (also compare [4]), the focal length of a lens or the lattice constant of a diffractive optical element can be changed. When additively manufacturing such a silicone element, the ferromagnetic material placement can be matched with the magnetic field. Furthermore, the particles should be positioned in a region of the optic which does not transmit radiation to avoid unwanted absorption and scattering.

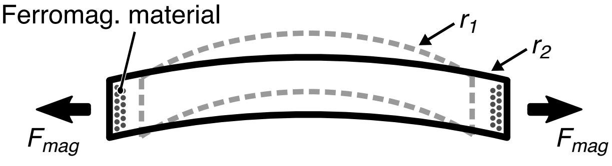

Fig. 1 *Variation of the curvature radius of a lens from r_1 to r_2 using magnetic actuation F_{mag}*

DGaO Proceedings 2021 – http://www.dgao-proceedings.de – ISSN: 1614-8436 – urn:nbn:de:0287-2021-A011-7
submitted: 04.11.2021 – published: 17.11.2021

Shape memory particles like iron-triazole-complexes increase their volume when exposed to heat. When cooled down again, they return to their original state. This microscopic effect translates to macroscopic structures as well. When inserted into a thin film silicone host matrix, an expansion of the silicone body occurs. Placing and pre-curling such a thin film on a flexible, non-expandable support structure such as aluminium foil enables an observable un-curling of the body with increasing temperature (Fig. 2). Optical thin film components such as blaze gratings can be deformed in a way that their diffraction pattern shifts when loaded with shape memory particles. Due to a lack of transparency of the particles, a placement of the particles near the aperture or a reflective application is required.

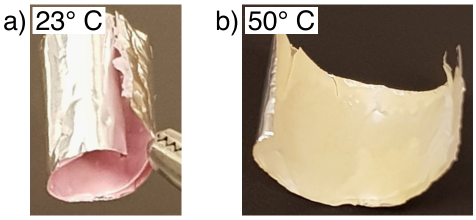

Fig. 2 *Curling of an iron-triazole thin film when heated up from a) room temperature to b) 50 °C (with kind permission of Arthur Sander, ACI, LUH)*

3 Challenges in functionalizing silicone optics using additive manufacturing

Additive manufacturing of nanoparticle-infused silicone optics starts with computational designing of the optical element. Afterwards it is sliced according to the layer thickness of the manufacturing process. While assigning multiple material properties to one object is trivial in most CAD software applications, many accessible slicers are not able to convert this data. Thus, the information has to be transferred manually to the extrusion unit containing the different silicone blends (silicone with and without nanoparticles).
Since the silicones are mixed before they reach the extrusion nozzle this local separation and therefore the temporal delay between adjustment of the nanoparticle concentration and printing of a voxel have to be considered. In addition the flow characteristics within the tube (different velocities in the cross section) can lead to a temporal broadening of e.g. an instant switching of the material properties.
Due to different densities, nanoparticles will sediment in the liquid silicone body. Due to their high specific weight this effect is significant for ferromagnetic particles and has to be compensated in the design process. After the silicone is cured the particles will remain in their positions.

4 Outlook

Once printed, the particle distribution has to be investigated experimentally. Computer tomographic methods for biological samples can be used to produce three-dimensional images of transparent elements with fluorescent nanoparticles. Upon obtaining knowledge about the particle distribution, these information can be extrapolated to other particle types. The information gained can be fed back into the computational design to compensate the delay between printing command and material extrusion as well as the temporal broadening (see Ch. 3).
To make use of the deformation capabilities of optics infused with ferromagnetic or shape memory particles a multi-physical simulation approach is required. Here a precise material model of the silicone including nonlinear elasticity is required.

5 Acknowledgments

This research has been funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy within the Cluster of Excellence PhoenixD (EXC 2122, Project ID 390833453), by the Ministry for Science and Culture of Lower Saxony (MWK) - School for Additive Manufacturing SAM and by EFRE - NBank within the project GROTESK - Additive Manufacturing of Optical, Thermal and Structural Components (ZW6-85018307, ZW6-85017815, ZW6-85017913, ZW6-85018048).

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