Smart Contact Lens Platform with a Deformed Active Artificial Iris

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ABSTRACT

This paper explores the challenges regarding the thermoforming of a deformable guest-host liquid crystal display within a smart contact lens. Focus was given to the finite element modelling of its fabrication, to find respective design rules. Such displays are thought to be used in vision correction applications (i.e. artificial iris).

1. INTRODUCTION

Nowadays, technological progress has been presented towards the development of the smart contact lens concept. The latter is foreseen to be applied in different fields ranging from biomedical control [1], signaling [2], and entertainment [3] to vision correction [4], among others. Within the vision correction applications, and besides the correction of focal length-related conditions (i.e. presbyopia), the development of an artificial iris operating in a dynamic way (i.e. emulating the function of a healthy eye) is currently being researched. Such device, if properly embedded in a smart contact lens architecture and made autonomous and self-regulated, would directly help more than 200000 individuals around the globe with some kind of iris deficiency [5]. Figure 1 presents an illustration of a smart contact lens to be used as an artificial iris including potential components such as a microcontroller, an organic photovoltaic, a wireless interface and an electro-optic component at the center of the lens.

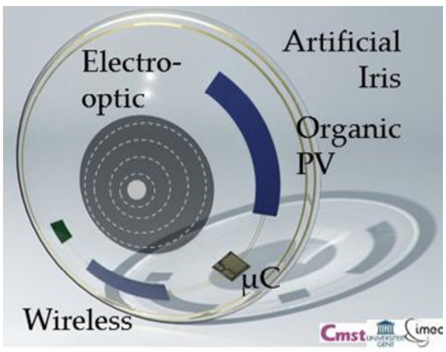

Fig. 1: Representation of the smart contact lens with an artificial iris LCD display, indicating the electro-optic component at the location of the iris.

The eye is generally divided in three main parts: the intraocular lens (allowing focusing on objects at different distances by changing its shape), the retina (the optically sensitive part of the eye where images are formed) and the iris-pupil arrangement. The iris is a variable size diaphragm responsible of adjusting the size of the pupil (the central opening) to regulate the amount of light entering the eye. The changes in size and light intensity are possible due to a combination of muscle fibers, autonomic nerves and several pigments (natural eye color). Figure 2 presents the contraction and dilatation of the iris-pupil arrangement when exposed to different levels of light intensity; from left to right: bright, normal and dim light. It is noted that the contraction is executed by the iris circular muscles, while the dilatation by the radial muscles. This particular role has been bio-mimetically replicated in the diaphragm of photographic cameras [6]. In humans, the pupil varies between radii of 1 mm and 4 mm according to ambient illuminance or autonomic response. Several conditions lead to iris deficiencies such as anatomic anomalies (aniridia, albinism), infections, ocular malignancies (melanoma, leiomoma), and/or neural disorders, all of them directly decreasing the pupillary response to light stimulus [7]. The latter is one of the main driving forces behind the development of an active system, which mimics the iris function allowing tunable light absorption at the pupil.

In this work, we present the smart contact lens platform with a guest-host liquid crystal display (GH-LCD) for iris conditions applications. Besides describing the different components in the system and their interactions, their thermoforming shaping from 2D to 3D was investigated and modeled using finite elements (COMSOL Multiphysics). An analysis of the stress/strain relationship during thermoforming was performed in order to understand the mechanical limitations of the platform/display and increase its robustness. The thermoforming method was proven to be a reliable way of fabricating such devices, especially when working with thermoplastic materials (i.e. polyethylene terephthalate, polyurethane, etc.) as main mechanical carriers. Besides a validated model of the thermoforming process, interesting trade-offs and design rules were extracted in order to determine maximum deformations at specific locations and final curvature of the lens, among others.

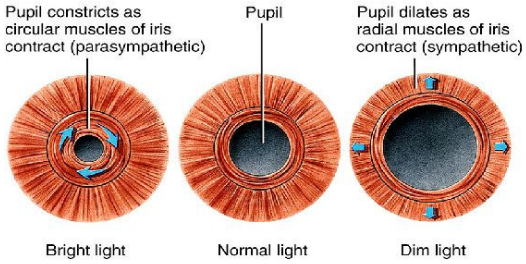

Fig. 2: Representation of iris contraction in response to light intensity [Adler's Physiology of the Eye]. The images show the circular muscles (parasympathetic) used to contract the iris and radial muscles (sympathetic) used to dilate the iris. The pupil is the center perforation.

2. GH-LCD MODULE

2.1 Design

The development of a guest-host liquid crystal display (GH-LCD) on polymeric substrates has been explored at CMST [4, 5] in order to realize a device capable of dynamically modifying the light intensity at the pupil, being actuated by the changes in ambience illumination. Liquid crystal molecules act as the "host" material and a suitable dye acts as the "guest" in this guest-host LCD. The oblong-shaped dye molecules follow the orientation of the LC molecules influenced by electric fields, thus making tunable light absorption possible. The display would be located at the center of the contact lens platform with a hollow center (i.e. to allow for oxygen transmission) and a combination of a concentric rings array in order to control the illumination in a diaphragm way (i.e. similar to the normal iris functionality). The polyethylene terephthalate (PET) based display was thermoformed into a spherical cap in order to fit the curvature of the eye. The process flow as well as the challenges regarding the filling of the liquid crystal chamber are described in [4]. Figure 3 shows states of a GH-LCD with concentric rings when being actuated. Although the contrast between the OFF and ON states is relatively low (1:2.4), the solution already provides substantial light dimming for potential patients with iris conditions.

2.2 GH-LCD fabrication

The fabrication of the GH-LCD happens on a flat surface in order to take advantage of standard processes offered by micro-fabrication (i.e. photolithography, material deposition, lamination, etc.). The process starts with the lamination of PET films (50-100 µm) onto a glass carrier, followed by consecutive photolithography processes to define the conductive, alignment and spacer layers. The spacers are designed as cylinders of 20 µm-wide and 10 µm-high. The latter is the gap of the cell. At the border of the lens a ring of glue is deposited (with an opening to fill the cell with liquid crystals) in order to fixate the bottom and top plates of the cell. After lamination of the referred plates, the glass carriers are removed and the circular shapes of the lenses are laser-ablated. At this point, the cell can be thermoformed into a spherical cap shape, and later filled (i.e. using the vacuum process) and sealed.

The completed GH-LCD cells can be transferred to a thermoplastic carrier (i.e. thermoplastic polyurethane - TPU) which forms the core of the smart contact lens platform. Such thermoformable platform can host other components such as silicon components, interconnections, RF antennas, etc.

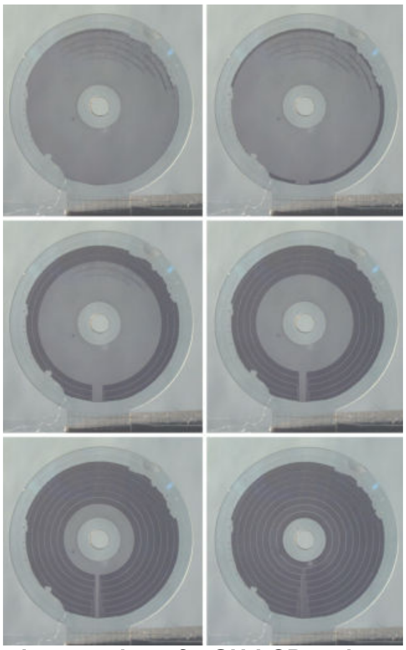

Fig. 3: Implementation of a GH-LCD active artificial iris by gradually darkening of concentric rings, which emulate the function of the iris [5, 6].

2.3 Thermoforming process

The thermoforming process involves the use of a metallic mold at a temperature higher than the glass transition temperature of the thermoplastic material used (PET and TPU > 80°C). In this work a working temperature of 120°C (at the interface between the mold and the thermoplastic) and a radius of curvature of 8 mm were chosen as parameters for the thermoforming. Once the desired temperature is reached, the top mold is moved down in a step lasting 5 seconds. Then, the mold is kept closed for 5 minutes, and finally, the mold is cooled down to room temperature and the cell is removed.

Figure 4 shows an implementation of the GH-LCD component after thermoforming and lamination to the thermoplastic mechanical carrier. The lamination to the carrier can happen before/after or during the thermoforming.

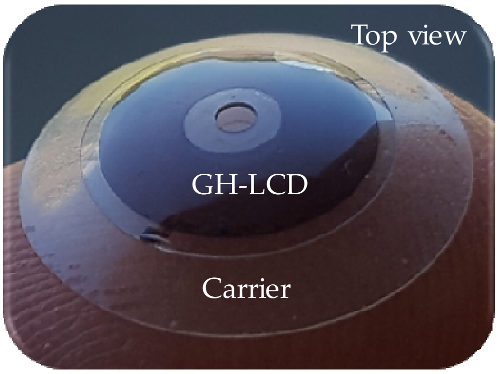

Fig. 4: Implementation of a GH-LCD after thermoforming with a thermoplastic mechanical carrier.

3. FINITE ELEMENT MODELING

3.1 Generalized Maxwell model

A finite element model (using the commercial software COMSOL Multiphysics) was developed to analyze the thermoforming of both the display and the mechanical carrier. The model will serve to extract design limitations and to predict lens curvature. Due to the viscoelastic nature of the polymers used (i.e. PET and TPU), the Generalized Maxwell viscoelastic model [8] and its constitutive equation (1) were used to represent the materials in the numerical simulations.

$$\sigma(t) = \epsilon \cdot \sum_{1}^{n} E_i \cdot exp\left(\frac{-t}{\tau_i}\right) \qquad (1)$$

Where, *σ(t)* is the stress dependent on time, *ε* is the stretch value, *E* is the Young's modulus and *τ* is the relaxation time, respectively.

3.2 Relaxation test

The material properties, describing the viscoelastic behavior, were extracted from experimental relaxation tests in literature (at 10% of constant strain) for the PET [8] and TPU [9], at 70°C and 200°C respectively. The Maxwell viscoelastic equations were fitted to the relaxation data using the Levenberg-Marquardt algorithm in a MATLAB script (using four independent relaxation coefficients). The corresponding fitted coefficients were then used as constitutive parameters in COMSOL simulations. Figure 5 shows the normalized shear stress (where G and G_{inst} are the bulk and instantaneous shear stress values, respectively) versus the relaxation time for the PET and TPU materials. The simulated stress levels during relaxation are in good agreement with the raw data, which validates the correct implementation of the material model. Such material model was used to implement a thermoforming simulation with a 3D space representation. The latter was validated with experimental data of strain after deformation and radius of curvature, with relative errors of 12±3% and 10±4%, respectively.

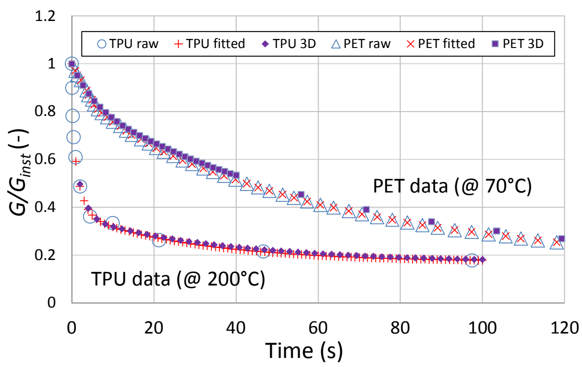

Fig. 5: Normalized shear stress (*G*) for PET and TPU during the relaxation test (10% of strain) versus time, comparing raw, fitted and simulated data.

3.3 Thermoforming model

Figure 6 shows the implementation of the thermoforming FEM model in COMSOL, indicating the different materials and structures of the GH-LCD cell (blue for the PET substrate and green for the spacers and ring of glue). For visualization purposes the top layer of the mold and cell are not shown. Figure 6a shows the initial flat state of the lens on top of the metallic mold, while Figures 6b-d show the deformed state of the lens. Furthermore, the lens is modeled as freestanding on top of the mold, which represents the conditions of the thermoforming experiment.

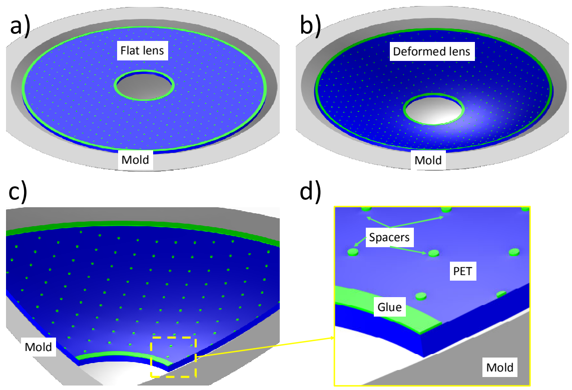

Fig. 6: Screen-shots from COMSOL. a) Initial flat position of the lens; b) Maximum deformation of the lens; c) ¼ symmetry of the deformed lens; and d) Close-up view of the deformed lens.

4. RESULTS

4.1 Mechanical deformation

The evolution of the mechanical parameters throughout the thermoforming were extracted using the implemented FEM model. For instance: the strain/stress (along meridian, hoop and/or vertical directions), the deformation profile and thus volumetric changes in the cell gap. Figure 7 represents the maximum strain developed in the structure when it is in contact with the top and bottom parts of the mold. Figures 7a-b indicates a tensile strain (positive value and red color in the figure) at the center of the lens, which is generated by the contact with the top part of the mold. A compressive strain (negative value and blue color in the figure) is generated close to the outer edge of the structure, due to the shrinkage in dimensions (deforming from a flat circle to a spherical cap). Taking into account a thickness of the PET substrates of 100 µm and a lens curvature of 8 mm, the maximum tensile and compressive strain values are 6% and 8%, respectively.

Figure 7c presents the strain levels along the vertical component. It is shown that the spacers experience a compressive strain (negative value), especially close to the center of the lens. The distributed spacers along the cell ensure a constant gap between the top and bottom layers. The homogeneity of the cell's gap, especially during display operation, is crucial to maintain a constant contrast. Furthermore, the gap plays a role in the trade-off between the cells' contrast and its driving voltage. The bigger the gap the higher the contrast and voltage, and vice versa. For the configuration we presented in Figure 6 and with a thermoforming at 120°C, the maximum compressive strain at the spacers (in the center region) is around 15%. The difference between compressive strains along the cell's surface is less than 5%.

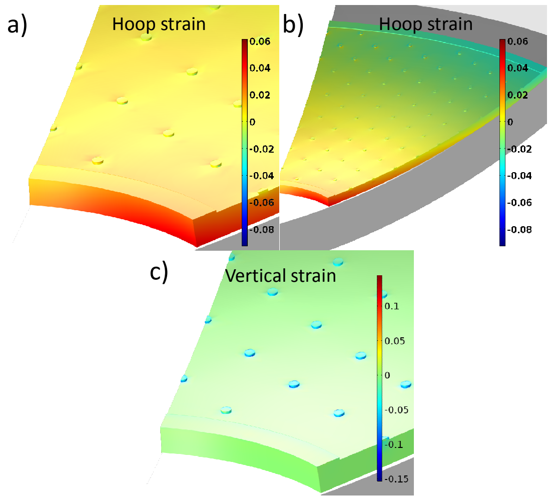

Fig. 7: Strain values at the bottom PET substrate and spacers along the: a-b) hoop direction and c) vertical direction.

4.2 Volume evolution of the cell

The relative change of the cell's volume during thermoforming was extracted from the FEM model, in order to optimize the structure design and prevent liquid crystal leakage. Figure 8 shows the evolution of the relative volume change of the cell with respect to time (for 5s @ 120°C) for two spacers' radii. The initial volume of the cells are 0.05 mm^3 and 0.047 mm^3, for 10 µm and 20 µm wide spacers, respectively. It is noted that during the thermoforming the volume is reduced by 10% and 2%, respectively. This change originates from the spacers compression shown in Figure 7c. The radius variation shown in Figure 8, demonstrates the potential of the FEM model to perform parametric optimization of the geometry throughout the thermoforming processing.

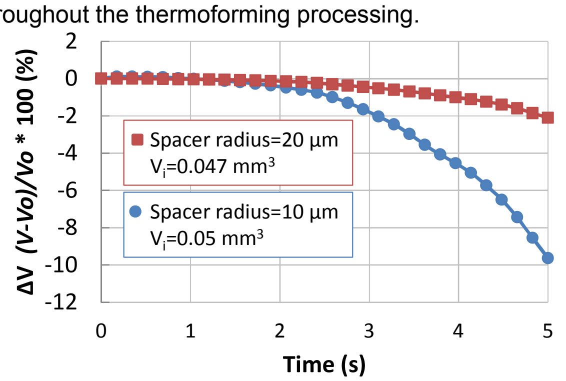

Fig. 8: Relative change in volume of the cell's cavity for a thermoforming step of 5s at 120°C.

5. CONSLUSIONS

This paper presented the implementation of a GH-LCD display for artificial iris applications within a smart contact lens. A FEM was implemented and validated which predicts the mechanical behavior of the display during thermoforming. It was found that maximum tensile strain along the hoop direction was located at the center of the lens (8%), while a compressive strain on the spacers along the vertical direction was around 15%. For two different spacers' radii (10 µm and 20 µm), the volume inside the cell was reduced by 10% and 2%, respectively. These models could be applied for diverse types of thermoforming steps of soft materials in order to enhance the mechanical integrity and proper component location.

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