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Optical quality study of refractive lenses made out of oxide glass using hot embossing

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HIGHLIGHTS

- We discuss hot embossing process to low-cost, low-volume lenses replication.
- We discuss the various process parameters that influences the lens characteristics.
- We analyze the geometrical and optical characteristics of the lenses.

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ABSTRACT

In this paper we discuss the fabrication of lenses made out of multi-component oxide glasses by using double-sided hot embossing to allow low-cost, low-volume replication of these lenses. We focus on the choice of the glass for both the stamps as well as for the molded component and we discuss the various process parameters of the hot embossing process that influences the lens characteristics. We also analyze the geometrical and optical characteristics of the lenses using state-of-the-art optical characterization tools. We find that lenses with radii of curvatures up to 8 mm for a diameter of 4.5 mm can be obtained under standard operation conditions (without vacuum) and that the stamp material should be further optimized in case lenses with higher radii of curvature need to be achieved.

1. Introduction

The current dynamic development of technology results from working on new materials. Such materials allow for fabricating components characterized by better performance in particular circumstances and extending the scope of their applications. New technologies, or those adapted from other domains, allow for a faster, more efficient and cost-effective production, they allow to reduce the size and improve the quality of the fabricated components. This type of development can also be noticed in the domain of optics. On the one hand, new materials with improved optical properties are being developed, which allows for smaller losses and operating in a wider wavelength range. On the other hand, there are materials whose properties are similar to those already available on the market, but cheaper to produce and easier to handle or manufacture. Progress in the methods of fabrication leads to producing smaller and lighter optical systems. It also allows for mass fabrication of optical elements, which reduces costs and ensures their widespread use. The key example of the latter will be, for instance, miniaturized camera lenses installed in mobile phones.

The primary aim of the research presented here was to develop oxide glasses that are easy to fabricate and cheap in production. Second, we aimed to produce diffractive and refractive optical elements working in the range from visible to midIR light, with the use of the simplest possible fabrication method, which is the hot embossing (HE) process. This paper briefly presents the results of our work on the selection of the oxide glasses and the modification of the HE technology. The main focus of the paper is on presenting the quality analysis of the fabricated lenses and how their parameters and quality changes in time during the fabrication for a large amount of elements.

2. Material selection and fabrication technology

There are a number of different technologies for the fabrication of optical components [1,2], among others: mechanical processing,

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lithography and ion technologies, injection molding and hot embossing. Mechanical processing is mainly used in the production of elements in the centimeter scale. Its main disadvantage is the time devoted to the grinding and polishing steps and high cost material processing. Lithography [3,4] and ion technologies [5] are best suited for manufacturing diffractive elements in the micro scale. They offer a very good precision of the micro-optical elements but these methods are expensive and they require specialized equipment. Injection molding [6,7] and hot embossing [2] are relatively cheap and both allow for high-volume manufacturing of elements in the micro and centimeter scale. These technologies are primarily used for the fabrication of polymer components [1,8], but HE and similar precision glass molding techniques can also be used for the fabrication of glass elements [1,9–15]. Compared to polymer HE, the HE in glass molding requires higher operating temperatures, larger pressure forces and longer production times. It is also critical to avoid glass crystallization, which may occur during heating, embossing or cooling of the element, and which renders the element optically useless.

Despite these problems the HE method is used for manufacturing both refractive [16] and diffractive [17] optical elements, as well as for planar waveguide elements [10] made from various types of glasses: borosilicate glasses [18] low-melting-temperature glasses [14], metallic glasses [9,15], chalcogenide glasses [10] and inorganic glasses [19]. In this paper we are testing if it is possible to simplify the hot embossing method for fabricating glass-based optical components, and lenses in particular. Thus, we use the HE without the protective atmosphere and at normal pressure.

The process of producing a single lens in the HE proceeds according to the following scheme (Fig. 1). In the first phase an appropriate glass sample is prepared. For this purpose, a glass block is formed, first using mechanical methods such as grinding and polishing. A cylinder is formed, whose diameter is about 110% of the targeted lens diameter. Then the cylinder is cut and polished into disks. Their thickness is selected in such a way that their volume is similar to the volume of the final element. Finally, a piece of glass prepared in this way is placed on the bottom half of the stamp.

During the second HE phase, both parts of the stamp and the glass disk are heated to the forming temperature. At this time, the glass softens and, thanks to its viscosity, it starts to assume a more spherical shape. In the next step, the upper stamp is lowered and pressed with a fixed pressure force onto the softened glass that is positioned onto the bottom stamp. The lens is formed. After a predetermined time the pressure is reduced, the stamps are separated and the temperature is reduced. Glass is separated from the stamp and is slowly cooled down to the room temperature in order not to introduce unnecessary stress. Obtained in this way, the lens requires no additional processing, such as polishing. Its quality can be examined in the third and last phase of the process.

Apart from the technical details like the speed of heating and cooling, the temperature of the embossing process and the force and time of pressure, there is also an important issue of selecting the glass material for the stamp and for the lens. The molded glass should neither wet the stamp, nor adhere to the stamp surface. This parameter of glass is important because the embossed lens must be easy to remove from the stamp, but also the glass should protect the surface of the stamp against erosion. On the other hand, we know from experimental practice that for every glass the right material for the stamp must be selected. The choice of the stamp materials includes [1] stainless steel, tungsten carbide, silicon carbide, aluminum nitride [20], often coated with additional layers like NiP, TiAlN [21] and ceramics [22].

In our study aiming to obtain lenses working from visible to MidIR range [10,15], we first employed an initial selection procedure with regard to the above-mentioned criteria and optical properties of glasses. Next, we chose for further tests a relatively cheap tungsten–tellurium–niobate glass labeled TWPN/I/6 (oxide composition synthesized in-house: WO_3 – 34.8%, Na_2O – 1.8%, TeO_2 – 60.3%, Nb_2O_5 – 3.1%). Its spectral transmission and viscosity characteristics are presented in Fig. 2 [11,16,23]. All experimental results presented later will relate to this particular glass. However, we obtained similar results for other composite metal-oxide-glasses, which is why we believe that the conclusions of the present are of a more general nature, and will apply irrespective of the selection of specific materials.

The desired shape of the stamp, i.e. the negative of each lens surface, was selected from commercial available concave lenses. The tests on glass adhesion of TWPN/I/6 glass to different metal, non-metal and ceramic materials allowed us to choose fused quartz glass as the best material for the stamp [17]. We tested other stamp materials [17], but the multicomponent oxide glasses adhered to the stamp surface and it was not possible to separate the lenses from a stamp. Sometimes, the surface of the stamp eroded, which did not allow for fabricating a larger number of lenses.

3. Lens fabrication

Having chosen the glass for the lens and the material for the stamp we optimized the hot embossing process. The most important factor was the temperature of forming the glass element. When the temperature is too low, the glass showed not ductile

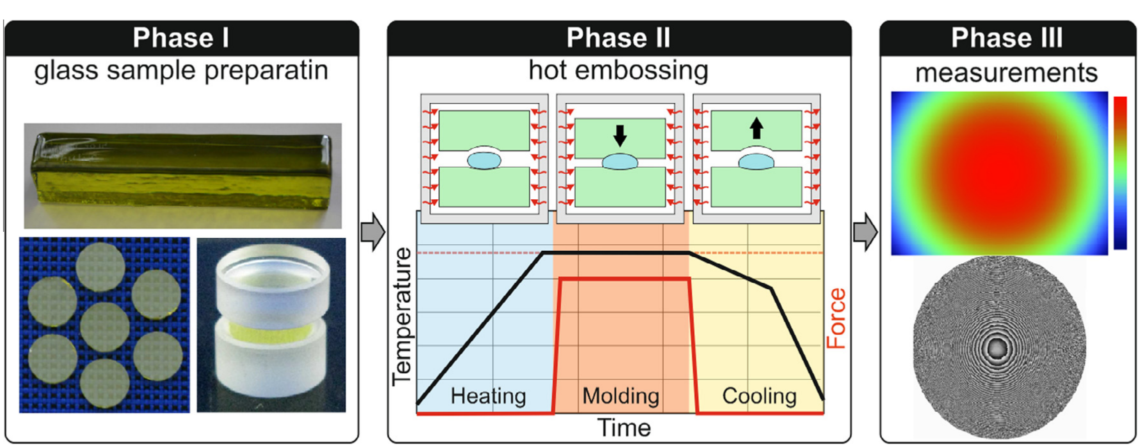

Fig. 1. The scheme for lens fabrication using the hot embossing process.