Fabrication of lens array using 3D printer and vacuum forming

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Abstract

We fabricated a lens array using a 3D printer, vacuum forming, and soft moulding techniques. A 3D printer was used to print the first prototype of the lens array, and vacuum forming was used to smooth the surface of the prototype with a melted plastic sheet. The smoothed prototype was used to create a soft mould using polydimethylsiloxane. Thermal epoxy was poured into a soft mould and allowed to harden to form transparent epoxy lens arrays. The fabricated lens array exhibited good images of objects and demonstrated its performance as a lens. In addition, the focal length of the lens arrays was varied by changing the radius of curvature of the prototype.

Keywords: lens, fabrication, vacuum forming, 3D printer, PDMS

1. Introduction

Traditionally, lenses are fabricated by polishing glass [1, 2], while microlenses are fabricated using a semiconductor process [3–7]. Glass polishing and semiconductor processing require high-precision techniques and expensive facilities. Recently, the precision of 3D printers has improved significantly, with some 3D printers now capable of fabricating optical components with nano-meter precision [8]. However, these types of 3D printers are extremely expensive for use in most laboratories and schools.

In this study, we propose a method for fabricating lens arrays that have relatively good quality and show the results of the fabrication and characterisation of the lenses through this method. The method we suggest here includes vacuum forming, originally reported in [9], where it was used to smooth the surface of a small prism array produced from a negative prototype fabricated using a 3D printer. The procedure in [9] involved pouring a mixture of a polydimethylsiloxane (PDMS) base and agent into the negative prototype and hardening it to make a transparent silicone (PDMS) rubber prism. In this study, we used a 3D printer and vacuum forming to produce a lens prototype and then used PDMS to create a negative silicone mould. Thermal epoxy was poured into the negative silicone mould and hardened to obtain the final hard and transparent epoxy lens. Making lenses can be more difficult than making prisms because lenses consist of curved surfaces instead of planes, and the final performance requires imaging capability rather than deflecting light. However, these lenses have wider applications and are more important for constructing optical systems than prisms. In addition, the epoxy used in making lenses has greater hardness and a higher refractive index than silicone rubber and thus frequently used in making optical components such as light-emitting diode (LED) lenses. The favourable properties of the epoxy may lead to wider applications of this fabrication method in the future. Finally, we measured the focal lengths of the fabricated lens arrays with various radii of curvature in the lens prototypes.

2. Methods

The process flow for creating the lens array, which was attempted in this study, is illustrated in Fig. 1. First, the 3D printer printed the first prototype of the lens array, as shown in Fig. 1(a). The 3D printer used in this experiment was a relatively inexpensive printer (ELEGOO MARS PRO). Ultraviolet (UV) images were obtained using a liquid crystal display to harden the UV resin layer by layer in increments of 0.05 mm. The vacuum-forming technique was applied to smooth the surface of the first lens prototype. The vacuum-forming machine used was a JT-18, and the first lens prototype was coated with a melted dental plastic sheet (HMT

GUOZIJIAN SPLINT) by vacuum action, as shown in Fig. 1(b). A mixture comprising PDMS base and curing agent was poured into the smoothed prototype to create a negative soft mould, as shown in Fig. 1(c). The hardened PDMS mould was separated from the prototype, as shown in Fig. 1(d), and thermal epoxy was poured into it and covered with a flat lid, as shown in Fig. 1(e). The flat lid was also made from PDMS, using a flat plastic sheet as a prototype. This lid is necessary to make the flat side of the plano-convex lens array. The hardened epoxy lens was separated from the PDMS mould to obtain a final hard and transparent lens, as shown in Fig. 1(f). The detailed process of making the PDMS mould and epoxy lenses followed the procedure used to make microlenses [7]. The intermediate and final products obtained from the lens-making process are shown in Fig. 2.

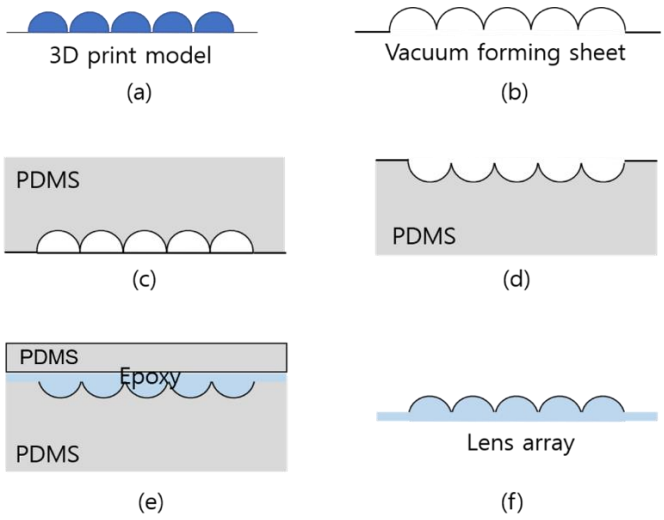


Fig. 1 Process flow involved in producing the lens array (a) making the first lens prototype using 3D printer (b) coating the prototype by vacuum forming (c) forming a negative PDMS mould (d) separating the PDMS mould from the lens prototype (e) pouring thermal epoxy into the PDMS mould (f) separating epoxy lens from the PDMS mould

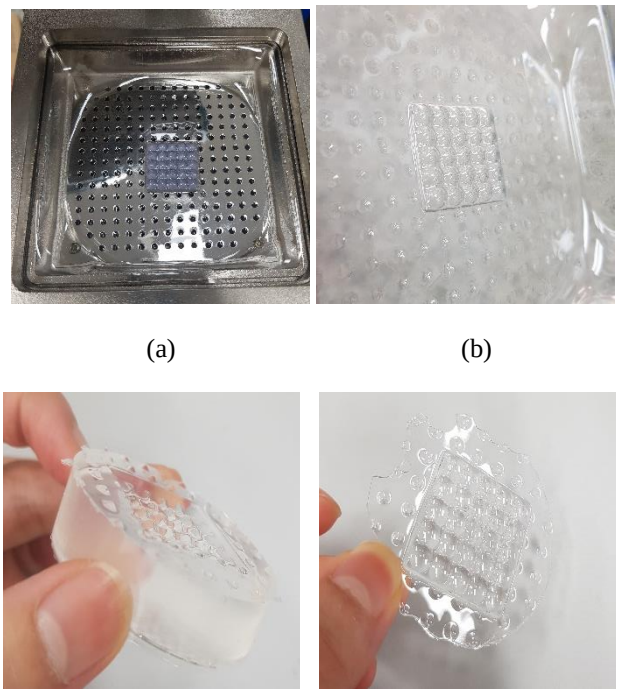


Fig. 2 Intermediate and final products from lens-making processes (a) the first lens prototype coated using vacuum forming machine (b) a lens prototype separated from the first prototype after vacuum forming (c) PDMS negative mould (d) a fabricated epoxy lens array after separation from the PDMS mould

An image of the letter ‘A’ was produced using the fabricated lenses to test if the lens array performed well as an imaging device, as seen in Fig. 3. The lens array produced clear and inverted images of the character ‘A’ when an upright letter ‘A’ printed on paper was placed at a certain distance from the lens. This clear image demonstrates the good performance of the fabricated lens as an imaging lens. In other words, ray bundles starting from a point in ‘A’ are refracted by the lens surface and converge to a small spot. If there is an error in the spherical surface of the fabricated lens, the image spot size formed by an object point becomes large and blurs the image.

The surface of the lens appeared very smooth to the naked eye and produced reflected images of the rectangular-shaped ceiling lamps, functioning like a convex mirror, as shown in Fig. 3(b), implying that the roughness of the surface is much smaller than the visible wavelength; the surface is optically smooth and produces very little scattering.

(a) (b)

Fig. 3 Images of the letter ‘A’ formed by a fabricated lens array: (a) an image produced by the lens array with the tapes on the side for fixing the lens on the supporting structure. (b) a magnified view of the image produced by one of the lenses in the array with a marking dot on the surface

3. Results and Discussion

Various shapes of lens prototypes and two different plastic sheets were tested to investigate the dependence between the shape of the first lens prototype and the final lens shape. It is important to evaluate the effects of prototype and processing on the final lens parameters, such as the focal length, because the corresponding knowledge can provide control and predictability over the final lens parameters. The lens prototypes used in the experiments are shown in Fig. 4. They have different lens diameters and heights, leading to different radii of curvature, except that lens c has the same parameters as lens b, but with holes between the lenses. Holes were added to assist the attachment of the plastic sheet to the prototype during the vacuum-forming process. The holes in the middle of the prototype may provide more air paths to the vacuum holes located at the bottom of the sample in contact with the vacuum plate of the machine. The radii of curvature for the lens prototypes were 2.69 mm, 3.63 mm, and 6.63 mm. First lens prototypes a, b, and c have 5 × 5 lens arrays, whereas lens prototype d has a 2 × 2 lens array with a large lens diameter. A larger radius of curvature implies a larger focal length, according to the lens maker’s formula. Therefore, if the final lens shape follows that of the first lens prototype, we can control the focal length of the lens by controlling the curvature of the lens prototype, which can be easily achieved using a 3D printer. A lens array was chosen as the prototype shape instead of a single lens to distinguish the advantages of the lens-making process proposed in this study from the conventional glass polishing method, by which is a difficult process.

We also introduced a variation in the process by using two different thicknesses of plastic sheets when coating the first prototype by vacuum forming. It is important to know the extent to which the thickness of the plastic sheet affects the final lens profile and focal length. The thicknesses tested were 0.6 mm and 1.0 mm, applied to prototypes a and b, respectively, creating two lenses from each prototype.

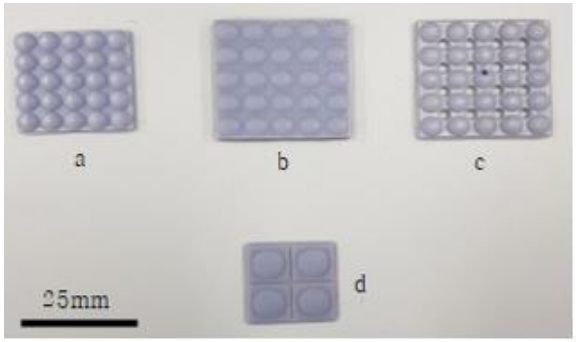


Fig. 4 Lens prototypes made by 3D printer: (a) r = 2.69 mm (h = 1.7 mm, d = 5.0 mm), (b) r = 3.63 mm (h = 1.0 mm, d = 5.0 mm), (c) r = 3.63 mm (h = 1.0 mm, d = 5.0 mm), and (d) r = 6.63 mm (h = 1.0 mm, d = 10.0 mm), where r, h and d are the radius of curvature, lens height, and lens diameter, respectively; prototype c has same lens profile as that of prototype b but has holes between the lenses.

The fabricated epoxy lens arrays are shown in Fig. 5. All the lens arrays had smooth surfaces, showing shiny reflections. Lens2 shows only a 5 × 3 array with two missing rows because it lacked epoxy resin during the PDMS mould filling process. However, the remaining lenses from the Lens2 prototype were sufficiently good for characterisation. As mentioned above, Lens1 and Lens2 were made from prototype a with different thicknesses of plastic sheet used for vacuum forming, whereas Lens3 and Lens4 were made from prototype b.

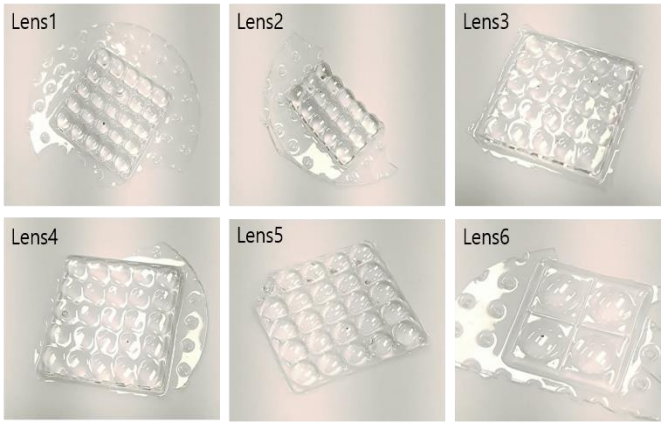


Fig. 5 Final epoxy lens arrays obtained from the first lens prototypes: Lens1 and Lens2 used prototype a with 0.6 mm and 1.0 mm thick plastic sheets, respectively; Lens3 and Lens4 used prototype b with 0.6 mm and 1.0 mm thick plastic sheets, respectively; Lens5 and Lens6 used prototypes c and d, respectively, with 1.0 mm thick plastic sheet.

The fabricated lens arrays were tested by imaging the character ‘A’ printed on white paper located at a certain

distance from the lens. The images obtained using the lens arrays are shown in Fig. 6. Magnified views of the images obtained from the central lenses of each type are shown in Fig. 7. Although some lenses far from the centre suffer distortion and blurring because of aberration, all the central lenses show clear inverted images of 'A,' demonstrating that all lens arrays function well as plano-convex lenses and have optically smooth spherical surfaces. Considering the basic function of a refractive lens is to collect rays starting from an object point and focus them onto a small spot, it is difficult to achieve this imaging capability without an optically smooth spherical surface. Therefore, our procedure to obtain a smooth spherical shape through 3D printing and vacuum forming and then transfer this lens shape into a transparent and hard epoxy lens was successful.

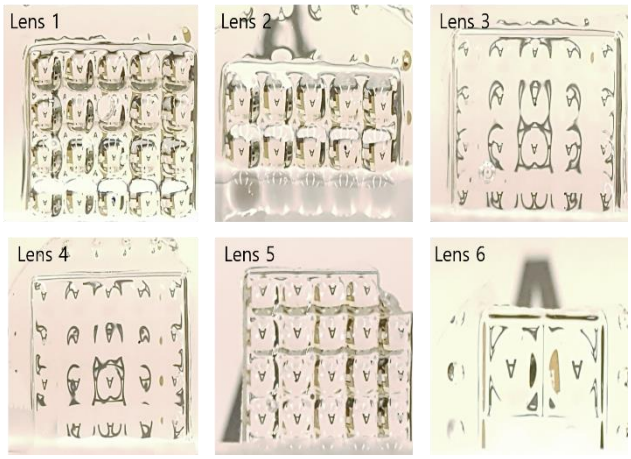
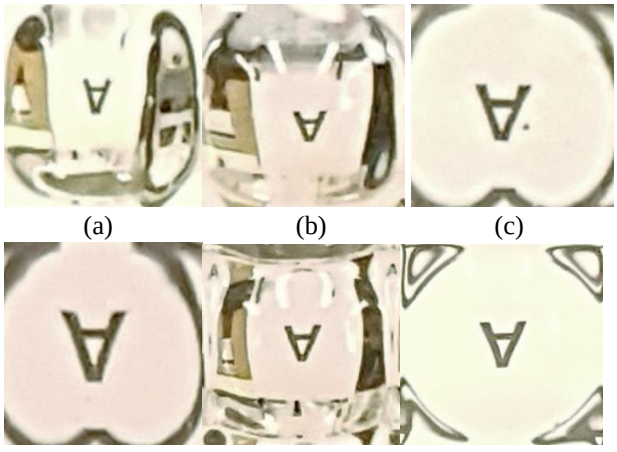


Fig. 6 Images of letter 'A' formed by the fabricated lens arrays


(a) (b) (c)

(d) (e) (f)

Fig. 7 Magnified views of the images of the letter 'A' formed by the fabricated lens arrays: (a) Lens1 (b) Lens2 (c) Lens3 (d) Lens4 (e) Lens5 (f) Lens6

Finally, we characterised the fabricated lens by measuring the focal length and investigated the effect of the lens prototype and thickness of the plastic sheet on the focal length. The focal length was measured using the Gaussian lens formula [10]. An object made with a plastic ruler and light source was imaged using a lens array fixed on a precision translation XYZ stage. A universal serial bus (USB) microscope observed the image of the object pattern. As a moving lens array with an XYZ stage can switch the focus of the USB microscope from the surface of the lens to the image formed by the lens, the distance between the lens and the image could be measured. Thus, the focal length of the lens can be calculated from the Gaussian lens formula using the measured image and object distances from the lens. The measured focal lengths of the lens arrays are summarised along with the other processing parameters listed in Table 1.

As shown in Table 1, the thickness of the plastic sheet did not affect the focal length when considering the measurement error, possibly implying that the coating thickness over the first prototype does not depend on the thickness of the plastic sheet but rather on the melting temperature or other parameters of the vacuum-forming process.

The correlation between the radius of curvature of the first prototype and the final focal length is presented in Table 1; a large radius of curvature results in a longer focal length. However, the exact relationship between them is not well explained by the lens maker's formula, according to which the radii of curvature calculated from the measured focal lengths are approximately 3.3, 3.4, 4.0, 4.0, 3.8, and 5.4 mm, respectively, for the lenses, as shown in Table 1. The epoxy was assumed to have a refractive index of approximately 1.5. However, the actual radii of curvature for the first prototype showed some differences. For a short focal length lens, the prototype has a smaller radius of curvature than the expected value from the focal length, which indicates a thicker plastic coating on the first prototype. However, for a lens with a longer focal length, the prototype had a larger radius of curvature than the expected value, implying that the coating process decreases the curvature of the final shape. This observation could serve as the foundation for future research. Nevertheless, we demonstrated that the proposed method of lens-making based on 3D printing and vacuum forming can be used to fabricate lens arrays with various focal lengths by changing the shape of the prototype with a 3D printer.

Table. 1. Measured focal lengths of the fabricated lens arrays

Lens num-ber	Lens Proto-type	Radius of curvature of the first lens prototype (mm)	Thickness of the plastic sheet used for vacuum-forming (mm)	Focal length (mm)
1	a	2.69	0.6	6.7
2	a	2.69	1.0	6.7
3	b	3.63	0.6	7.9
4	b	3.63	1.0	7.9
5	c	3.63	1.0	7.6
6	d	6.63	1.0	10.7

4. Conclusions

We proposed and experimentally demonstrated a method for fabricating lens arrays using a 3D printer, vacuum forming, and PDMS soft moulding techniques. The 3D printer was used to make the first prototype of the lens arrays with various lens diameters and heights. The different lens shape parameters result in various radii of curvature and focal lengths. The vacuum-forming process smoothed the rough surface of the first prototype by coating it with a melted plastic sheet. The smoothed plastic prototype was separated from the first prototype and used to create a negative PDMS mould. Thermal epoxy was poured into the PDMS mould and hardened to create a transparent and hard epoxy lens array.

The fabricated lens arrays functioned well as imaging lenses and exhibited clear inverted images of the letter 'A' printed on paper, indicating that the fabricated lens had an optically smooth spherical surface with insignificant scattering from the surface. In addition, the image formed by reflection from the lens surface indicates that the surface is optically smooth.

The focal lengths of the fabricated lens arrays were measured using the Gaussian lens formula. It was found that the thickness of the plastic sheets (0.6 mm and 1.0 mm) did not significantly affect the focal lengths of the final lens arrays. However, the difference in the radius of curvature of the first prototype changed the focal length. A larger radius of curvature in the first lens prototype results in a larger focal length of the final lens. This tendency can be used to control the focal length of the final lens by changing the curvature of the first prototype, which can easily be achieved using a 3D printer. The relationship between the radius of curvature of the first prototype and the final focal length did not obey the lens maker's formula exactly and was difficult to determine because the coating with a plastic sheet during vacuum-forming seemed to change the profile of the first prototype in a complicated manner depending on the curvature or the geometry of the first prototype.

In summary, the proposed method of making lens arrays based on 3D printers, vacuum-forming, and PDMS moulds can provide an economical way of making complicated optical components such as lens arrays, which is difficult with conventional glass-polishing methods. We expect that this will be helpful in many areas of research and optics education.

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