Preparation of Fresnel Lenses by Radiation Cast Polymerization

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Synopsis

Preparation of Fresnel lenses was investigated applying radiation polymerization of methyl methacrylate prepolymer systems containing polyfunctional monomers. Line focus Fresnel lenses 75 × 75 cm could be prepared in very short time cycles with sufficient exactness by radiation cast polymerization, preferably at low temperatures. Preparation of Fresnel lenses could be carried out also very easily and efficiently by printing the soft plastic prepolymer sheet with a Fresnel lenses mold and then curing it by irradiation.

INTRODUCTION

Cast polymerization is one of the conventional production processes for organic glass articles of rather high quality. However, hitherto the casting process has been known for its poor efficiency due to its lengthy cycle in comparison with injection and compression methods. That is, the casting cycle has been long in order to complete the polymerization and so avoid the formation of defects such as strain, stress foam, and surface shrinkage.

This characteristic has made the casting method unsuitable for the mass production of organic glass articles. However, we have studied the casting process[1–4] by radiation polymerization in a supercooled state using glass-forming monomers and prepolymers which show small volume shrinkage and large polymerizability in this state. It was found that casting by irradiation could be carried out without the formation of defects in a remarkably shorter cycle than previously. This process can be applied to various kinds of organic glass articles—not only glazing materials, but also lenses and other mold products.

As is well known, plastic material is advantageous for its lightness, ease of shaping, cheapness, and availability mass production in comparison with inorganic glass. From this point of view, the most preferable and appropriate use of organic glass might be in the field of nonspherical surface lenses. These advantages could be fully utilized, if a new, high-efficiency process were developed to produce high-quality cast articles for this field.

We have tried to develop an efficient preparation process for Fresnel lenses, considering them typical of the nonspherical lenses which are expected to be important for solar energy utilization in the near future. However, an efficient preparation technique for large-scale mass production of Fresnel lenses is not now known. We report here a study of a new preparation process for such lenses by radiation casting and describe the properties of the lenses obtained.

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EXPERIMENTAL

All monomers used were industrial reagent-grade quality. Polymerization was carried out in a casting frame by γ-ray irradiation from a 100,000 Ci ^{60}Co source at temperatures controlled by refrigerator systems.

The specifications of the mold for the linear Fresnel lens used are as follows:

Aperture (draw up in two rows)	150 cm
Length and width for one side	75 cm
Focal distance	150 cm
Width of focal line	~2 cm

The strain formation was checked with a photoelastic strain gauge with polarized plates.

The penetration of soft-gel prepolymer was measured in accordance with ASTM-D217-50.

The distribution of the line-focus position was determined by a focus-point test using an He–Ne gas laser beam, which was designed to move from side to side of Fresnel lens at right angles to the Fresnel lines.

RESULTS AND DISCUSSION

Preparation of Fresnel Lenses by Cast Polymerization of Fluid Prepolymer

Fluid prepolymer for casting was obtained by dissolving polymethyl methacrylate into monomers consisting of methyl methacrylate and polyfunctional monomers or by partially polymerizing the above monomeric system by low-dose irradiation. The latter method is more convenient than the former, because the troublesome operation of dissolving the polymer into monomer homogeneously while keeping the solution free from air foam can be avoided in the latter. Moreover, it was found that control of the desired conversion and viscosity of prepolymer was done easily and safely by irradiation. Because control of the reaction rate is easier due to the relatively lower temperatures in polymerization, a broader range of reaction conditions can be used to control the rate in irradiation method than in catalytic polymerization. The fluid prepolymer was then charged into the casting frame, which was constructed with one flat, reinforced glass plate and one steel Fresnel mold plate, [Fig. 1(a)]. The cast polymerization was carried out by γ-ray irradiation at various temperatures, and the results are summarized in Table I.

According to these results, 75 × 75-cm Fresnel lenses with good surface flatness, that is, apparently homogeneous and with clear pitches, could be obtained by irradiation at low temperatures below $-10°C$, with very short casting times, e.g., 2 ~ 4 hr.

Preparation of Fresnel Lenses by Mold Polymerization of Soft Prepolymer

It is expected that gel-state prepolymer may be treated in the casting process more easily and conveniently than fluid prepolymer. Furthermore, casting in a horizontally set state or in a free state with no frame for continuous processing

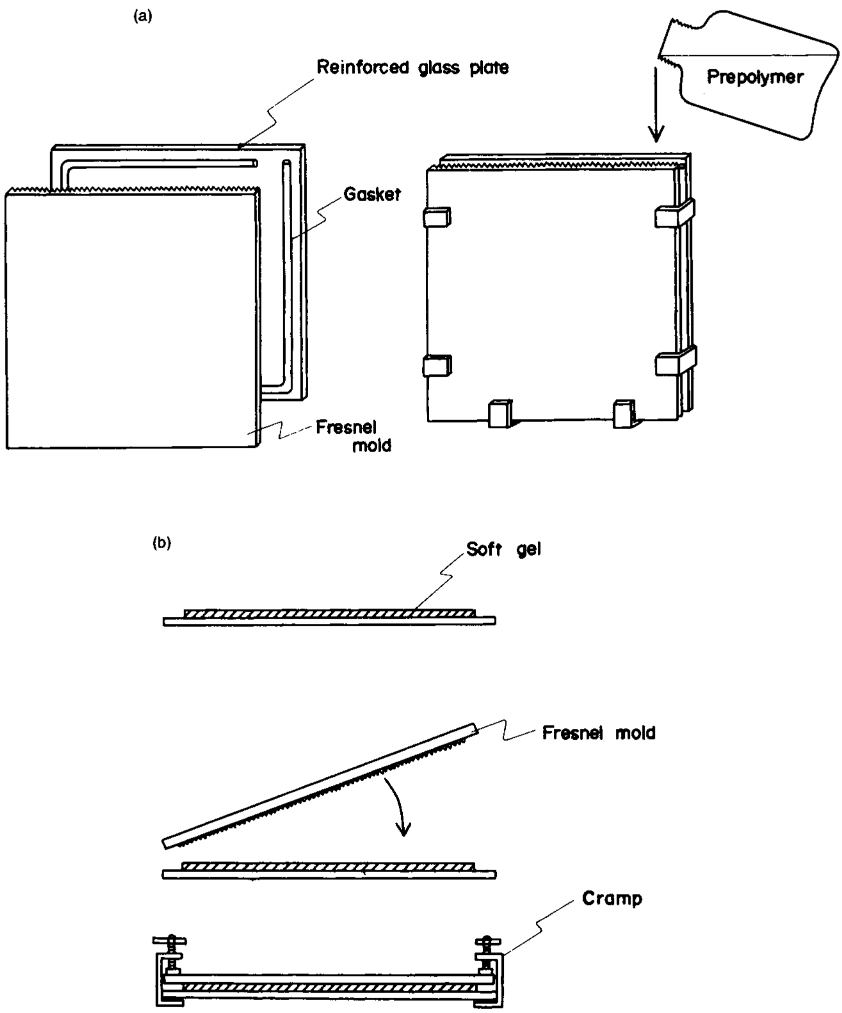

Fig. 1. Preparation of line-focus Fresnel lenses: (a) casting method and (b) soft-gel method.

is possible at room temperatures using soft-gel prepolymer. It was found that plastic and moldable soft-gel prepolymer was prepared effectively by irradiation of selected fluid prepolymer consisting of methyl methacrylate prepolymer and polyfunctional monomer. According to this method, control of conversion and viscosity of prepolymer suitable for molding is attained very easily, which is difficult in catalytic polymerization due to the accelerated polymerization rate at relatively higher temperatures. Some results for preparation of soft-gel prepolymer are listed in Table II.

Using these soft-gel prepolymers, mold polymerization of Fresnel lenses was carried out by pressing the gel prepolymer sheet lightly between a molding frame consisting of a Fresnel pitched steel plane and a flat, reinforced glass plane and irradiating it to complete polymerization, as illustrated in Figure 1(b).

The operation of molding and releasing the polymer is very simple and efficient in this method. Some results of the mold polymerization of Fresnel lenes by this method are listed in Table III. According to these results, 15 × 15-cm Fresnel

TABLE I
Fresnel Lenses Produced by Radiation Cast Polymerization[a]

Composition,[b] %	Dose, R	Irradiation Time,	Irradiation Temp., C	Strain	Surface Flatness
MMA:PMMA:A4G					
67.5:22.5:10.0	3.4×10^5	2	20	No	Poor
67.5:22.5:10.0	3.4×10^5	2	20	No	Poor
67.5:22.5:10.0	5.1×10^5	3	0	No	Poor
67.5:22.5:10.0	6.8×10^5	4	−10	No	Good
67.5:22.5:10.0	6.8×10^5	4	−10	No	Good
67.5:22.5:10.0	6.8×10^5	4	−20	No	Good
MMA:PMMA					
75:25	2.1×10^5	1.25	20		
75:25	3.4×10^5	2	0	Yes	Poor
75:25	5.1×10^5	2	−10	Yes	Good
75:25	5.1×10^5	3	−20	No	Good
75:25	8.5×10^5	5	−40	No	Good

[a] Dose rate, 1.7×10^5 R/hr; sample thickness, 10 mm.
[b] MMA, methyl methacrylate; PMMA, —; A4G, tetraethyleneglycol diacrylate.

TABLE II
Preparation of Soft-Gel for Fresnel Lenses

Composition,[a] %	Dose, R	Polymer, %	Penetration, 10^{-1} mm
MMA:PMMA:A4G			
67.5:22.5:10	2.0×10^5	46.1	106–108
67.5:22.5:10	2.5×10^5	52.8	45–50
MMA:PMMA:A2G			
67.5:22.5:10	2.0×10^5	43.6	121–126
71.2:23.8: 5	1.55×10^5	50.8	101–105
MMA:PMMA:P9G			
67.5:22.5:10	2.0×10^5	35.8	189–190
71.2:23.8: 5	1.9×10^5	47.1	99–101
MMA:PMMA:TMPT			
67.5:22.5:10	1.0×10^5	47.7	41–47
MMA:PMMA:TMET			
67.5:22.5:10	1.0×10^5	50.5	30–38
MMA:PMMA:P2G			
74.2:24.8: 1	1.75×10^5	51.5	108–118
67.5:22.5:10	1.2×10^5	43.9	105–110

[a] MMA, methyl methacrylate; PMMA, —; A4G, tetraethyleneglycol diacrylate; A2G, diethyleneglycol diacrylate; P9G, polypropyleneglycol dimethacrylate; TMPT, trimethylolpropane trimethacrylate; TMET, trimethylolethane trimethacrylate; P2G, dipropyleneglycol dimethacrylate.

lenses having good surface quality were obtained by irradiation of only $\sim 3.5 \times 10^5$ R in ~2.25 hr. However, in the molding of 75 × 75-cm lenses, the pitches in the center of the sample were not clear, perhaps due to some release of prepolymer from the pitched mold in that the area. The cause of this might be due to warping of the mold in the center resulting from setting it upright for irradiation. This fault is improved and smooth lenses are obtained by using gel prepolymer having a somewhat greater thickness in center part, corresponding to the warping of the mold.

TABLE III
Preparation of Fresnel Lenses from Soft Gel[a]

Size, cm	1st Irradiation Dose rate, R/hr	1st Irradiation Time, hr	2nd Irradiation Dose rate, R/hr	2nd Irradiation Time, hr	Strain	Surface Flatness
15 × 15	1.5×10^5	1.25	2.0×10^5	1.00	No	Good
15 × 15	1.7×10^5	1.25	1.0×10^5	1.00	No	Good
75 × 75	1.5×10^5	1.25	1.0×10^5	1.00	No	Poor
75 × 75	1.5×10^5	1.25	1.0×10^5	1.00	No	Poor

[a] First step, preparation of soft gel; second step, curing of Fresnel lens.

Focus Exactness and Energy Collection Functions of Prepared Fresnel Lenses

The focus exactness and energy collection functions of 75 × 75-cm Fresnel lenses prepared by the irradiation method were investigated.

Figure 2 shows the distribution of line focus position as determined by a focus point test using an He–Ne gas laser beam through each pitch of the sample. According to the results, focus positions at every pitch are concentrated within ±1.0 cm in width for the pitches within about 45 cm from the end of sample but diverge by more than 1.0 cm for pitches further than 45 cm from the end of the sample. This decrease in focus exactness is probably due to an insufficiently exact mold, since there is no reason to believe that the precision of casting differs between the center and outer parts of the lens. However, this focus distribution within ± 1.0 in a lens 45 cm wide may be permissible for practical use in solar energy collection.

The heat collection function of Fresnel lenses was measured by pyrheliometer, and the results are shown in Figure 3. According to these results, in the center position of focus, the collected heat energy per unit area reached about 20 times that of the nonfocused position. That is, multiplication of energy concentration is estimated to be 20 times in this line focus lens. The temperature of the central focus position of a heat pipe reached 173°C after 20 min of solar energy collection.

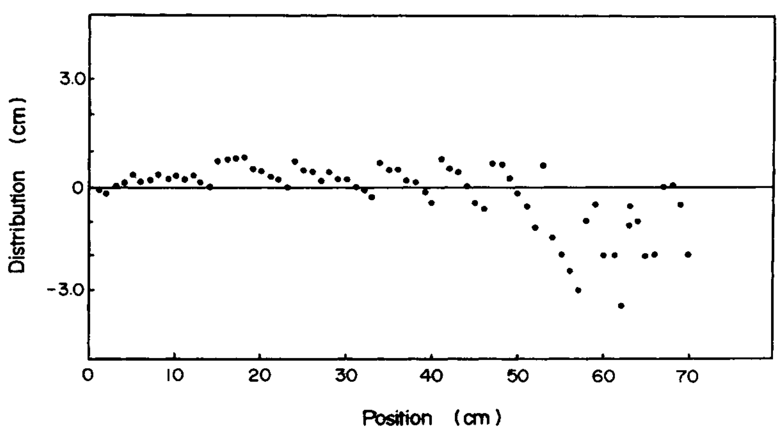

Fig. 2. Distribution of line focus position.

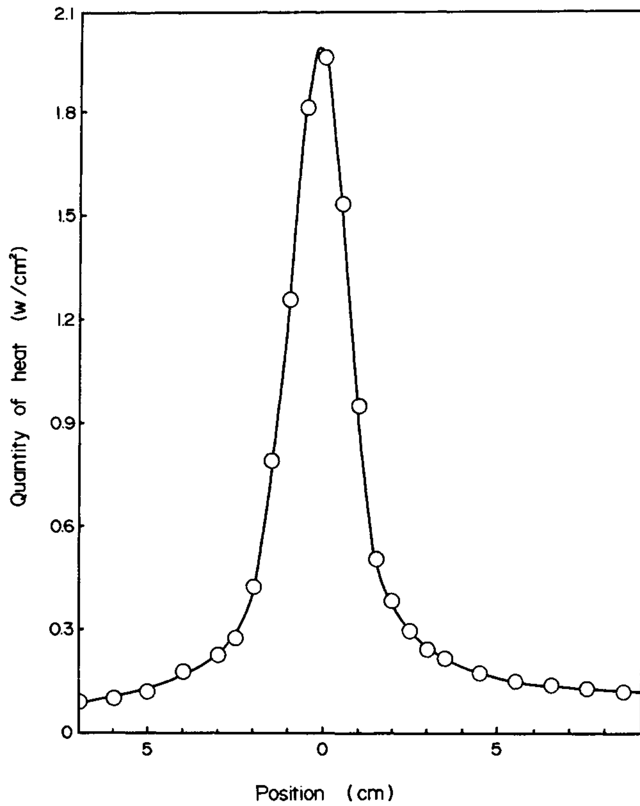

Fig. 3. Heat-collection function of the Fresnel lenses (heat at nonfocus position was 0.103W/cm^2).

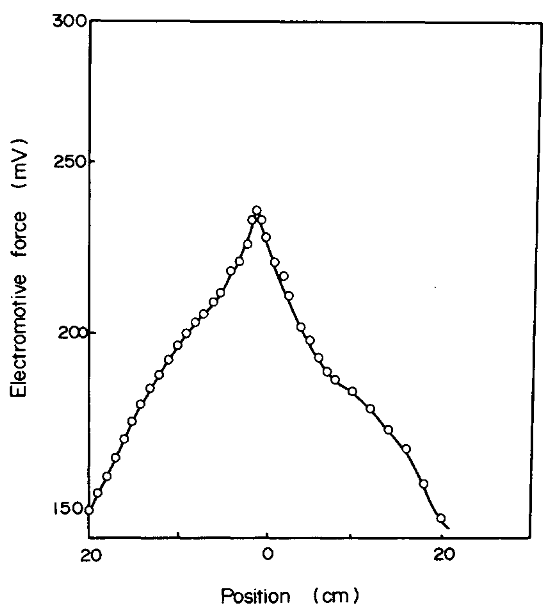

Fig. 4. Electromotive force of the line focus Fresnel lenses.

The results of electromotive force measurements by photodiode are shown in Figure 4. The electromotive force in central focus position increased to 160% of that in the nonfocused position despite that the photodiode used was very sensitive.

In conclusion, it was found that an efficient and convenient preparation of scale-upped Fresnel lenses with line focus as well as point focus was possible using radiation polymerization, especially by prepolymerization and curing polymerization of soft-gel prepolymer. These irradiation techniques are certainly useful for the mass production of Fresnel lenses for solar energy collector.

SUMMARY

Preparation methods of Fresnel lenses by radiation-induced polymerization were investigated. It was found that line focus Fresnel lenses 75 × 75 cm could be prepared conveniently by irradiation cast polymerization of a methyl methacrylate prepolymer system containing polyfunctional monomer. Irradiation at low temperatures was preferable for achieving the homogeneous and smooth Fresnel lenses having clearly "printed" pitches.

Another preparation method for Fresnel lenses was proposed. That is, Fresnel lenses could be prepared very efficiently and simply by "printing" the previously prepared soft plastic gel prepolymer sheet with a pitched mold and then curing it by irradiation in the mold. Some properties of formed Fresnel lenses such as focus distribution and solar energy collecting functions were also investigated. Focus distribution was quite good, and the concentrated energy multiplication was 20 times.

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