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# Techniques of fabrication of Fresnel lenses

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**Abstract**

This paper describes the extensive experimental effort which led to the fabrication of Fresnel lenses. A detailed account of the techniques and processes involved in the compression moulding of these lenses is given.

**Key words :** Fresnel lenses, solar energy concentrators.

## 1. Introduction

The wide range[1] application of the Fresnel lenses in audiovisual equipment and other uses has attracted the attention of academic and scientific community and commercial organisations. The recent application of these lenses, both spherical and cylindrical, as solar energy concentrators has added a new dimension to this developmental activity.

Miller *et al*[2] and Boettner *et al*[3] have given a brief historical account of Fresnel lenses and their applications. Over the years, no significant developments in the technology of fabrication of these lenses took place because of difficulties of moulding with glass conforming to fine pattern of grooves on large diameter formats. The introduction of moulding in plastics and the availability of mouldable transparent plastic materials has ushered in a fresh activity in the fabrication of Fresnel lenses. The present day Fresnel lenses in plastics are actively competing with glass optical lenses in applications where sharp imaging is not required. Recently, however, it is claimed that plastic Fresnel lenses fabricated under accurately controlled conditions are capable of resolutions up to 100 lines mm. With the present sophisticated Fresnel master making techniques and precision plastic moulding methods it has become possible to produce Fresnel configurations conforming to special types such as positive and negative aspheric lenses, positive cylindrical lenses and many others.

The technology of fabrication of Frensel lenses consists of three independent and essential processes :

1. The optical design of Fresnel surface.
2. The fabrication of metal masters by using numerically controlled machines and special tools.
3. The fabrication of plastic Fresnel lenses by moulding processes.

While the first process deals with the theory of Fresnel grooves in deriving the data of each groove by using a computer, the second and the third involve complicated technological processes.

The efforts of several Indian scientific and technical institutions to fabricate Fresnel masters and lenses by utilising the commonly available facilities in machine shops resulted in a limited success only. Keeping in view the growing demand for Fresnel lenses and realising the need for indigenisation of the manufacture of these lenses with excellent optical qualities, the Department of Science and Technology has sponsored the project " Design, development and fabrication of Frensel Condensers (lenses) " for execution by the Indian Institute of Science.

This project involves the fabrication of Fresnel lenses and Fresnel masters. The first phase of this project deals only with the work connected with the replication of plastic Fresnel lenses from available masters. This paper describes the developmental programme which culminated in the fabrication of a large number of Fresnel lenses using imported masters with the following optical properties (Fig. 1):

| | |
|---|---|
| Focal lengths | : 13·5″ and 8·5″ |
| Diameter (aperture) | : 14″ |
| Grooves | : 2 grooves/mm. |

## 2. Fabrication of Fresnel lenses

### 2.1. *Equipment*

The replication of Fresnel lenses from metal masters can be done either by compression moulding or injection moulding.

The injection moulded products are inferior[4] in performance due to occurrence of flow patterns which cause a certain degree of localised scattering affecting the transmission. This phenomenon is, probably, due to the mounting of the metal dies in a vertical direction and the irregular flow of the injected molten plastic over the groove pattern. In addition, as injection moulding presses of high capacity tonnage are not readily available in the country, for vertical operation a compression moulding press was used.

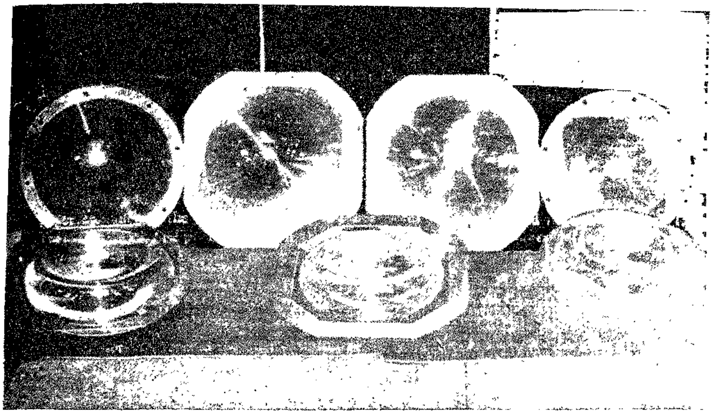

FIG. 1. Fresnel lenses fabricated at the Indian Institute of Science.

## 2.2. *Compression press requirements*

The large size of the Fresnel masters and the characteristics of the moulding material require a compression press with the following facilities:

(*a*) 250 ton load,

(*b*) Built-in arrangements for steam heating and water cooling.

(*c*) Minimum (almost zero) daylight between the plattens.

A 300 ton press available at a nearby rubber moulding factory was hired and modified suitably (Fig. 2). It is a vertical, 4 column upstroke press provided with a 4 daylight system. The press is fitted with five plattens of dimension 810 × 800 × 45 mm each with facility for heating the plattens which are provided with through holes for passing high pressure steam. Steam heating of the plattens ensures uniform temperature throughout the surface of the platten. The movement of the platten during downstroke is restricted by 4 side stops such that each daylight is of 100 mm gap. During the upstroke the daylights are closed one by one from the bottom to almost zero individual daylights. The working cycle of the press is controlled through a hydraulic valve which is activated by a lever type handle. The working pressure can be varied by adjusting a control valve near the hydraulic oil tank and can be read by a pressure gauge to indicate the valve in tons/square inch.

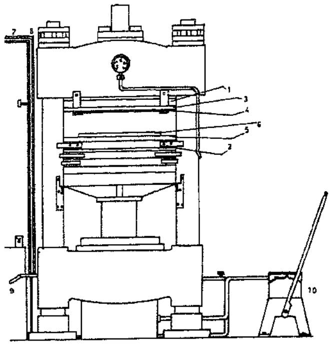


FIG. 2. Hydraulic Press. 1. Top platten, 2. Bottom platten, 3. Top plate, 4. Highly polished sheet, 5. Bottom plate, 6. Fresnel Master, 7. High pressure steam line, 8. Heat insulation, 9. Water line, 10. Hydraulic control valve.

## 2.3. *Steam boiler*

High pressure steam is necessary for heating the plattens to a maximum temperature of about 170° C. The steam is supplied at a pressure of 15 kg/cm$^2$ by a vaporax boiler fired by furnace oil and brought to the compression press by an adequately insulated overhead steam pipe provided with two valves to control the flow of steam through the pipe.

## 2.4. *Modification to the press*

As the surfaces of the top and bottom plattens of the press were likely to get damaged during the compression they were protected by fitting mild steel plates. The bottom plate carries the top die by means of two metal strips. The two surfaces of the bottom plate are smooth finished for intimate contact with the platten on one side and the Fresnel master die on the other. Fresnel master is rigidly held to the top surface of the bottom plate by means of four clamps. To prevent back firing of steam during the cooling stage and to control the flow of water, the press was connected to a water line with control valves.

## 2.5. *Fresnel metal master and the flat die*

A Fresnel lens consists of a thin plastic sheet one surface of which carries the Fresnel grooves and the other a plane surface. Two dies are, therefore, required. The Fresnel master which contains the grooves is made the bottom die. The grooves conform to the following equation (Fig. 3).

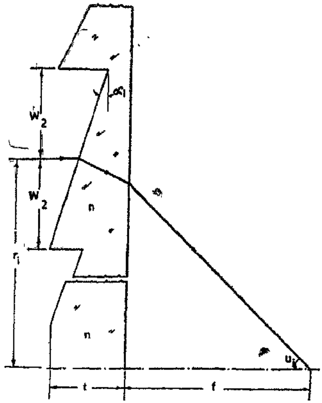


FIG. 3. Ray path through a Fresenel groove.

$$f \tan U_i = r - (t - \tfrac{1}{2} W \tan \alpha_i) \tan \{\arcsin [(\sin U_i)/n]\}$$

where

$U_i$ is the angle which the refracted ray makes with the axis after refraction at $i$th groove.

$\alpha_i$ is angle of the $i$th groove.

$r_i$ is the distance of the $i$th groove from the axis.

$W$ is the distance between the two grooves.

$t$ is the thickness of the lens.

$f$ is the focal distance of the lens.

$n$ is the refractive index of the lens.

These grooves are cut on special brass by using NC machine with linear $X$, $Y$ move-nent and rotation of the tool.

The top die is an optically polished and electroplated glazed sheet of dimensions 24″ × 18″ × 1/16″. This reproduces the plane surface of the plastic Fresnel lens. A brass ring of dimensions 450 × 450 × 3 mm, fabricated with both surfaces polished, has been fitted on to the Fresnel master by 4 mild steel dovel pins preventing the ring from any rotation or shift with respect to the master during compression. This ring is an essential component to obtain the required thickness of the Fresnel lens during the compression cycle,

## 3. Moulding material

Thermoplastic materials such as polymethylmethacrylate, polycarbonate, etc., are used for moulding of Fresnel lenses. The more commonly used material PMMA (in sheet or granule form), a polycarbonate and a high temperature thermoplastic, requires a high working temperature and load for compression. PMMA granule is preferred to sheet as the sheet has the following disadvantages :

1. In the thermoplastic stage the flow of the material is not free.
2. The evolved gases and vapours cannot freely escape during the compression process.
3. Elaborate evacuation equipment is required to suck out the evolving gases.

In addition, the good optical properties of granules such as transparency (refractive index 1·49; Abbe number = 59·0), low absorption losses and good UV absorption characteristics recommend themselves for fabrication of quality lenses. A particular formulation (No. 99141–7N) with these properties has been imported for use in this work.

## 4. Processing techniques

### 4.1. *Preparatory stage*

The metal master and the glazed sheet are thoroughly cleaned and heated to about 100° C to drive off any moisture trapped in the grooves. Simultaneously, a weighed quantity of the plastic material is sieved and pre-heated to about 120° C. The master is removed from the platten after heating. The plastic granules are spread over the master uniformly without any voids, so that the granule layer thickness is decidedly more than the thickness of the brass ring which is fitted on to the metal master. The master with the material is loaded on to the press for further pre-heating.

### 4.2. *Compression cycle*

During the pre-heating period the plastic material passes through the glass transition temperature to thermo-elastic state. When the master assembly reaches the required temperature the compression load is applied by closing the daylight till the pressure gauge shows the required pressure. The heating of the master assembly is continued under this pressure, during which the material is transformed into a viscous state capable of flowing and filling the grooves of the master. This duration called the hot curing period constitutes the most crucial and critical time interval in which any change in the temperature or pressure from the prescribed optimum values will bring about drastic irreversible changes in the properties of the moulded product. The cold curing period which follows the hot curing period consists of two stages. During the first stage the operating high temperature falls to about glass transition temperature under pressure and in the second stage the master assembly cools down to the room temperature without the pressure. During this cold curing period the product under compression stabilises retaining the pattern impressed on it during compression. The most important point to note is that the compression pressure is released at or near about the transition temperature of the material.

### 4.3. *Product release*

After the compression cycle the product should come out of the master with ease and without any breakage. Smooth release of product from the mould has been found to depend primarily on (*a*) the smooth surface of Fresnel grooves having no hooks or burrs which tend to anchor the plastic material, (*b*) proper hot and cold curing and (*c*) pressure release at appropriate temperatures.

## 5. Testing of the final product lenses

The lens is visually inspected for defects, air bubbles, transmission, surface irregularities and glaze. An experimental set-up consisting of a thermocouple and a meter is arranged for measuring temperature of the unclouded, midnoon, sun radiation collected by the lens at its focus. A consistent value of a temperature more than 1200° C has been considered as a ready-made test of the performance of the lenses which could be considered good.

## 6. Results and discussion

Several experimental product Fresnel lenses of focal lengths of 8·5″ and 13·5″ were replicated to determine the optimum parameters of working temperature, working pressure, hot and cold curing periods Some of the experimental results after optimisation are presented in Table I. These data are common to both 8·5″ and 13·5″ masters as the area of these masters is same. With weight of the material and working pressure as fixed parameters the working temperature has been varied from 155° C to 170° C in steps of 5° C. With each of these working temperatures the variations in the pre-heating time, hot and cold curing periods have been studied. At the optimal conditions, the lenses have not developed any air bubbles, brittleness and mould release was easy.

## 7. Conclusions

The experimental data obtained from several product lenses led to the following conclusions :

1. The working temperature should be as high as possible.
2. The pressure should be released at about the transition temperature during the cold curing period.
3. The pre-heating time and hot curing period should be about 45–50 and 8 minutes respectively.
4. Mould release depends on the above three criteria and on a working pressure of about 1 ton per sq. inch and also on high working temperatures.

5. Glaze and transparency essentially depend on high working temperatures.
6. Brittleness may be traced to low working temperature, high working pressure, inadequate hot and cold curing periods.
7. Air bubbles are due to air locking during the closing and opening of daylights and also inappropriate hot and cold curing periods. In addition, non-uniform spreading of granules during the charging might result in air bubbles.

The experiments wer. conducted at a maximum temperature of 170° C only. Higher temperatures up to 190° C are likely to improve the glaze and transparency of the lenses.

## 8. Acknowledgement

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**Table I**

**Experimental results using Fresnel lens master**

Focal length: 8·5″, Weight of material: 480 grams, Working pressure: 1 Tonne/Sq. inch.

| Sl. No. | Working temperature (°C) | Pre-heating time (Min) | Hot curing time (Min) | Cooling time | | REMARKS | |
|---|---|---|---|---|---|---|---|
| | | | | With pressure (Min) | Without pressure (Min) | Transparency | Glaze |
| 1. | 155 | 32 | 10 | 8 | 12 | Not good | Not good |
| 2. | 155 | 32 | 8 | 8 | 12 | Not good | Not good |
| 3. | 155 | 32 | 5 | 8 | 12 | Not good | Not good |
| 4. | 160 | 38 | 10 | 8 | 12 | Not good | Not good |
| 5. | 160 | 38 | 8 | 8 | 12 | Not good | Not good |
| 6. | 160 | 38 | 5 | 8 | 12 | Not good | Not good |
| 7. | 165 | 42 | 10 | 8 | 12 | good | good |
| 8. | 165 | 42 | 8 | 8 | 12 | good | good |
| 9. | 165 | 42 | 5 | 8 | 12 | good | good |
| 10. | 170 | 48 | 10 | 8 | 12 | good | good |
| 11. | 170 | 48 | 8 | 8 | 12 | good | good |
| 12. | 170 | 50 | 5 | 8 | 12 | good | good |

The 'good' lenses show easy mould release, no brittleness and no air bubbles.