Proc. of SPIE Vol. 2600, Design, Fabrication, and Applications of Precision Plastic Optics, ed. X Ning, R T Hebert (Dec 1995) Copyright SPIE

Precision plastic optics applications from design to assembly

Claude Tribastone, Charles Gardner, and William G. Peck
Opkor Inc., 740 Driving Park Avenue, Rochester, New York 14613

ABSTRACT

Versatility, low cost, limited materials, and unfamiliar manufacturing and assembly processes generate opportunities, obstacles and confusion in the transition from glass to high volume plastic lens assemblies. From concept to final assembly, many factors must be considered. Different experiences and capabilities lead to different preferences among injection molding shops for materials, surface types, mechanical features, doublet assembly, subassembly processes, vacuum coatings, final assemblies, etc. Because the low cost and great versatility of polymer optics make them very attractive, care must be taken to ensure that appropriate quality standards can be met. The authors' experiences are drawn upon to address a number of such issues, from design through assembly and testing, from manually stuffed clam shells and tubes to diffractive optical element eyepieces and robot assembled endoscopes.

Keywords: plastic optics, polymer optics, injection molding, lens design, volume production, diffractive optics, aspherics, vacuum coating, plastic, robotic assembly, endoscopes, laparoscopes

1. INTRODUCTION

This paper is intended to introduce optical and mechanical engineers to the enhanced capabilities of modern injection molded polymer optics. We also hope to alert them to the engineering issues of the transition to injection molded optics from glass optics. The particular issues discussed are only a sampling of the changes in engineering approach required to take maximum advantage of the paradigm shift. Molders often see optical designs that have been "finalized" by the customer and carried through to mechanical parts design with optics that are much more difficult and expensive than necessary (or impossible) to mold, such as the ubiquitous, very strong, plano convex asphere. Many of the "preferred" solutions to these problems will vary from one molding house to another, but the worst problems are problems for all molders. Thus it is recommended that the engineering team establish and maintain contact with at least one molding house from the inception of a project.

2. CONCEPT, OPTICAL AND MECHANICAL DESIGN

Many engineering issues specifically related to polymer optics can be recognized in the early stages of design.

2.1 Inherently plastic optical products

Many molded plastic optics projects are motivated by cost, some by versatility. The distinction is rarely clear cut, as the functionality is normally attainable in glass, but frequently at prohibitive cost. Thus it is possible to fabricate glass lenses with excellent diffractive surfaces, but perhaps at impractical cost for large scale production. Endoscopes with all glass optics are too expensive for the single use market. Some of the properties that may define inherently plastic optical products are:

- low cost
- high production volume
- light weight
- unusual or difficult configurations
  - diffractive optical elements
  - aspherics
  - array lenses
  - Fresnel surfaces
  - inset facets/multiple surfaces
  - integral mounts and spacers
  - non circular shapes
  - single piece multi-element
  - lensed prisms

The issues are whether the volume will cover tooling for the targeted price, and whether appropriate quality can be attained.

2.2 Surface figure

Most optical molders can not achieve 10 fringe surfaces on 3 inch diameter parts, except perhaps for plano windows. Yet they may come close to 1/2 fringe irregularity on smaller parts. Strong surfaces cause difficulty both in molding and assembly. The ideal plastic lens shape, for good control of surface figure, is uniform thickness. Since more power per element is usually desired, the designer should attempt to keep the edge thickness to center thickness ratio as close as possible to unity. As with glass, splitting an element may improve both the aberrations and the ease of manufacture and assembly. Prisms for use in a porro prism binocular assembly will usually be too large to attain the quality that is normally expected in the application. A similar prism, 1 cm on a side with integral spherical surfaces, may be excellent for a detector system. Maintaining good figure on both surfaces is difficult for lenses with a single plano surface, inappropriately located discontinuities, non-circular shapes, etc. Typically difficult to mold to precision tolerances are:

planos
prisms
non-circular elements
strong surfaces or elements
high ratios of center to edge thickness
diameters greater than 3 to 4 inches

The optical designer can normally determine preliminary irregularity tolerances for a first order (Gaussian) layout, based on the acceptable axial astigmatism and the ratio of axial beam diameter to clear aperture.

$$\text{relative irregularity tolerance} = (\text{clear aperture/axial beam diameter})^2$$

Discussion drawings of the elements, with powers and apertures based on the paraxial layout, and reasonable shapes and edges, can be prepared and sent to various molders for comments on feasibility to help direct the design effort.

2.3 Materials

The quality of optical plastics has been upgraded substantially by the chemical companies, primarily because of the high volume of the cd-rom market. New high purity materials and multilayer vacuum coatings have improved clarity to the point that endoscopes containing more than two dozen plastic elements have excellent color balance and transmission.

Environmental factors must be investigated. Condenser lenses must withstand the heat from the light source, yet be reasonable to mold. Plastics have greater thermal expansion and much greater thermal variation of index of refraction than glass. Shift of focus must be acceptably small for fixed focus systems operated across a wide temperature range.

2.4 Optical coatings

Multilayer anti-reflective, reflective, beam splitters, and various other multilayer dielectric and metallic vacuum coatings can be deposited on plastic lenses. In most cases vacuum coatings also improve the abrasion resistance of the plastic substrates. As element size increases, coating costs can dominate molding costs.

2.5 Cemented components

Cemented doublets and triplets are now produced in high volume from plastic elements.

2.6 Flange considerations

Some molders prefer to work with flanges around the lens, as in Figure 1. In many cases the flange can extend beyond the surface vertex of a convex surface and protect the surface from damage when the lens is placed on a table or in a tray. In this case, small airspaces may be achieved by the flanges without requiring additional spacers. If the molder does not incorporate flanges, the same airspace may result in a spacer requirement which is too thin, particularly for robotic assembly. Thus the most manufacturable value of airspace may be dependent on whether or not the lenses will be flanged. The same issue may arise if the system is to be prototyped in glass prior to tooling. Careful mechanical design, aided and abetted by the optical designer, can allow the use of the same spacer for slightly different airspaces, reducing component count and potential errors.

2.8 Aspheric surfaces

The use of aspheric surfaces entails increased costs and risks, particularly with imaging systems. They tempt designers to solve their problems at one surface, often too strong to mold well, which can not be measured quickly and accurately for process development or quality assurance. This may be acceptable for simple detector systems, but must be used with care for imaging systems. The designer can reduce the risk by spending sufficient effort on the system design to make the aspheric element as manufacturable as possible, and by minimizing the departure from a sphere. As with strong lenses, adding an element to a system is often justified if it eliminates or reduces the power of an aspheric lens.

2.9 Diffractive surfaces

Plastic diffractive elements, with an emphasis on correcting chromatic aberrations, are being used quite successfully in the visible spectrum, as well as in the infrared. Unlike aspheres, they offer the enormous advantage of reducing element count while simultaneously reducing the power of the remaining elements.

3. TOOLING AND MANUFACTURE

Molding, coating, cementing, assembly, and test all require well designed, accurate tooling for best system performance.

3.1 Clean lenses

Dirt is a serious surface quality flaw in many situations, especially when a surface is to be coated, cemented, or located near an image plane. It is simpler and less expensive to keep a lens clean than it is to clean it. Operator attitude, positive airflow workstations, and appropriate containers are key to clean lenses. Placing lenses in coating adapters at the molding machine reduces contamination and damage from handling, as well as handling cost. Enough adapters must be available to handle the molding machine, provide a buffer to the coater, fill the coater, and provide a buffer to assembly or cementing.

3.2 Edge contact situations

While the edge contact airspace is a very useful lens design tool, especially when a tight airspace tolerance must be held, the approval of the molding house should be obtained as soon as its possible use becomes apparent. There may be serious issues with regard to the strength of the edge and how well the two elements cup together. See Figures 2 and 3. A concave surface in the final part is molded from a convex surface on the optical insert, which can not be machined to form a flat for the concave surface, as with a concave glass surface. See Figures 4 and 5. Therefore, the contacting edge is (hopefully) a protruding ring.

3.3 Flanges

The flange may save a mechanical mount in instances where insufficient edge thickness for gating occurs before the desired tube diameter is reached. It also provides a buffer zone against birefringence and cylindrical irregularity ("gate draw") around the gate. A gate flat (Figure 4.) allows removal of the lens from the runner without protrusions outside the desired diameter or additional machining, with its associated contamination. Additional "dummy" gate flats and other flange features may be used to assist in identification for assembly, whether manual or robotic.

Elaborate flange designs facilitate proper filling of the lens and ejection from the mold. They also provide cement wells at cemented surfaces and reference flats for vacuum chucking in the cementing operation.

3.4 Aspheres

Eliminating aspheres may simplify testing, normally shortens tooling and process development time, and improves manufacturing robustness. Hand polished aspheres may impact both cosmetics and surface figure.

3.5 Cementing

Semi-automated cementing fixtures maintain alignment by mechanical fit, automatically dispense the cement, bring the parts together, UV cure the cement, and open for removal of the doublet. With typical curing times, a single operator can normally insert singlets, remove doublets, and provide quality assurance for two such fixtures.

3.6 Testing

Classical optical shop procedures such as operator inspection, interferometric testing of surfaces, double pass testing of assemblies, MTF testing, spectrophotometer testing of vacuum coatings, and functional testing are used for process control and quality assurance.

3.7 Manual assembly

Most classical manual assembly procedures, including insertion into precision molded clam shells, can be applied to plastic. In addition, mounting features such as tabs, screw holes, and flanges can lead to simpler, less expensive optical subassemblies and final assemblies.

3.7 Robotic assembly

Pick and place robot arms, assisted by machine vision systems to verify part and orientation, stuff 10 optical subassemblies, comprised of 32 optical elements, down a foot long tube along with a number of stops and spacers. Some of the optical parts come from the same coating adapters they were placed in at the molding machine.

A large (about 12 feet by 12 feet) enclosed, positive airflow, robot area has conveyor belts to load optical subassemblies in trays and a large buffering table where the operator loads empty tubes and removes stuffed tubes for focusing. The operator console and focusing station flank the opening to the buffering table. Several reels, similar in appearance to magnetic tape reels, provide mylar tape to automatic punches that manufacture and provide the robot arm with various size aperture stops and field stops as needed. A number of bowls gravity feed an assortment of spacers to pickup areas for the arm.

The arm retrieves optical subassemblies from the appropriate tray on the conveyor belts and places them in front of a vision system for verification of part and orientation. In the case of relay subassemblies, the proper orientation alternates with each subassembly. If the orientation of the part is not correct for the current position, the part is laid down in a fixture that flips it end for end, and retrieved again by the arm.

The operator adds eyepiece assemblies to stuffed tubes taken from the buffer table and focuses them in a fixture that provides real time MTF readout to aid focusing and provide quality assurance. When the operator is satisfied that the scope is acceptable the eyepiece is cemented to the tube.

A significant downside is that automation equipment providers seem prone to outrageous price gouging for spares and maintenance service.

4. CONCLUSION

The future for plastic optics in the US is, perhaps, more exciting and challenging than the past was for glass. Tube stuffers can bring the high yields and efficiencies of electronics board stuffers to optics. For this to happen, engineers must learn to work even more closely with the molding houses than they worked with the glass shops in the past.

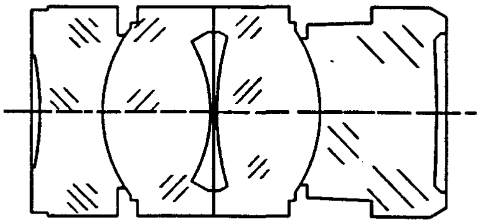

FIGURE 1. FLANGE SPACED LENSES

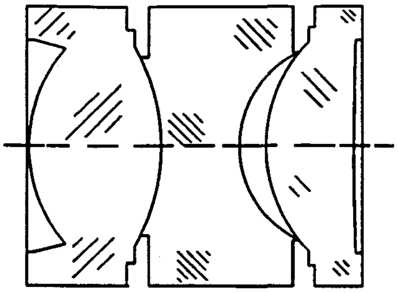

FIGURE 2. EDGE CONTACT ASSEMBLY

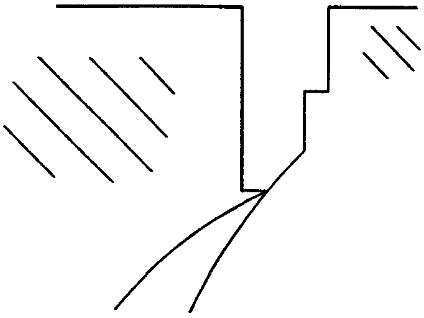

FIGURE 3. EDGE CONTACT DETAIL

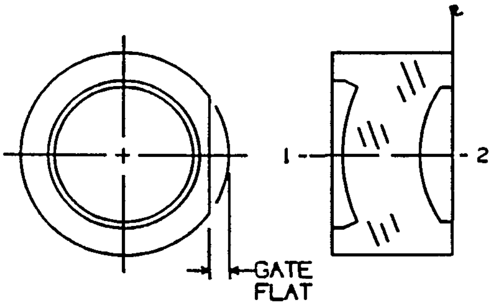

FIGURE 4. MENISCUS LENS WITH GATE FLAT

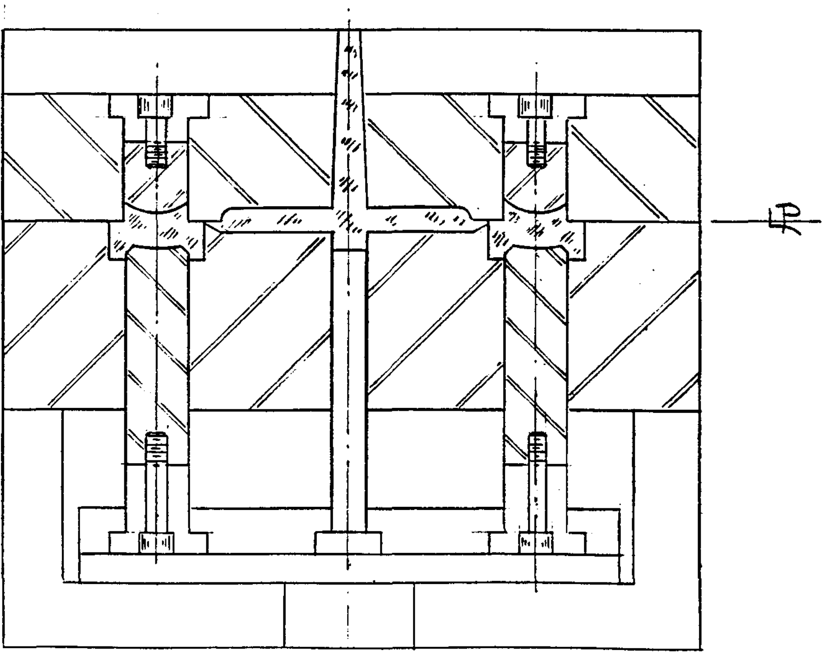

FIGURE 5. OPTICAL MOLD SCHEMATIC