Proc. of SPIE Vol. 0181, Contemporary Optical Systems & Components Specifications, ed. Robert E. Fischer (Apr 1979) Copyright SPIE

Specifying glass and plastic optics—what's the difference?

John D. Lytle
M U Engineering & Manufacturing, Inc
Mt View, California

What's So Special About Plastic Optics?

Plastic optics have come a long way since the first lens was injection molded many years ago; in fact today, the replacement of conventional optical components seems to be one of the least exciting aspects of polymer optics. Like waveguide optics, holographic optics, and coherent optics, plastic optics offers freedoms and options simply not available in conventional glass optics. This is not to say that plastic is not well suited to substituting for glass in many ordinary applications. The real virtues of plastic become clear, however, when one takes advantage of the medium to produce a totally unconventional component. Fig. 1 depicts a precision polygon having internal facets - a part whose manufacture is not possible using conventional glassworking techniques.

Aspheric surfaces, usually considered to be last resort options, are not only possible, but little more expensive than simple spherical ones, thus making available variables for the lens design process which most designers consider to be a luxury. The rear surface of element No. 4 in Fig. 2 departs almost 200 μm from the nearest spherical surface, and makes possible marked improvements in field flatness in a plastic optical system which provides usable contrast well beyond 100 l/mm over a 20 degree full field at F/2.8, 28mm EFL.

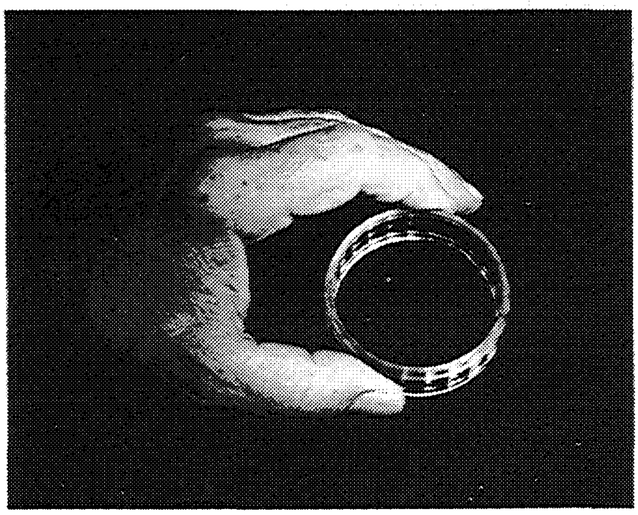

Fig. 1. A polygon having 24 internal facets.

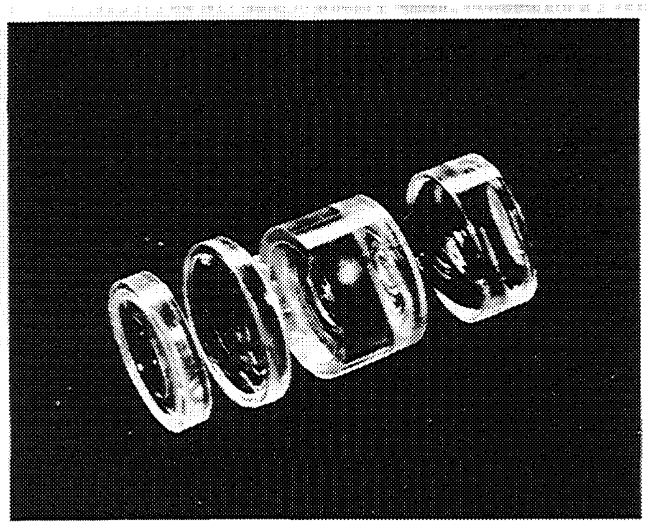

Fig. 2. Exploded view of a 4-element optical system whose final surface is strongly aspheric.

The inclusion of special mechanical features into the lens itself may eliminate the need for separate spacers, secondary shaping operations, or mechanical carriers. The lens element shown in Fig. 3 is molded in square form with "grab tabs" to facilitate insertion into a mechanical assembly. Unequal thickness tabs prevent damage which might occur as a result of wrong-way insertion.

Arrays such as the system of cylinder surfaces shown in the parts in Fig. 4 are molded very economically, although the cost of a similar glass part would be prohibitive.

Conventional types of components (Fig. 5) are of course possible in plastic, and are often used in situations where weight, shock, or other special problems dictate the use of

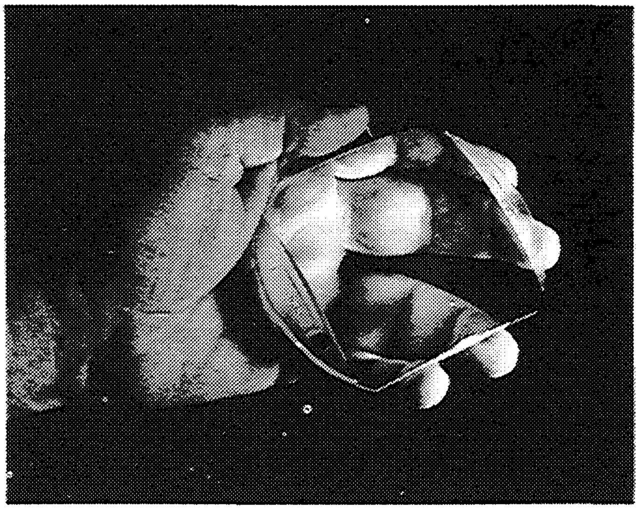

Fig. 3. A larger plastic optical element incorporating special mechanical features.

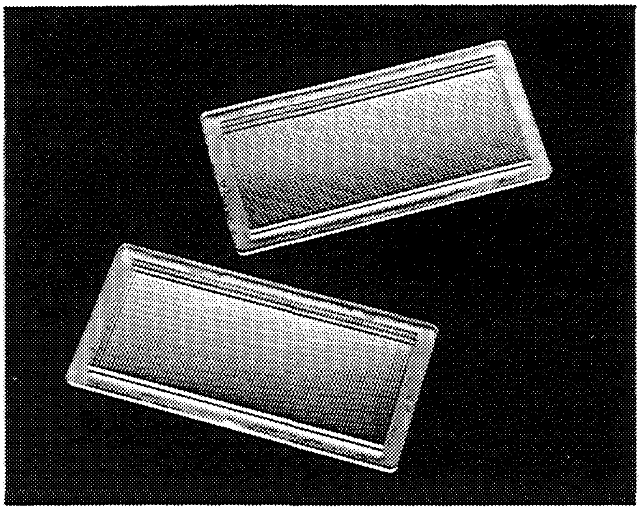

Fig. 4. A pair of matched arrays of cylinder surfaces.

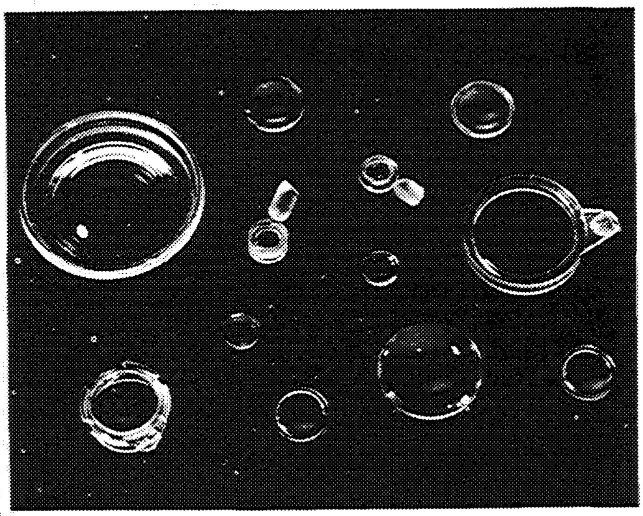

Fig. 5. A collection of conventional optical components implemented in plastic.

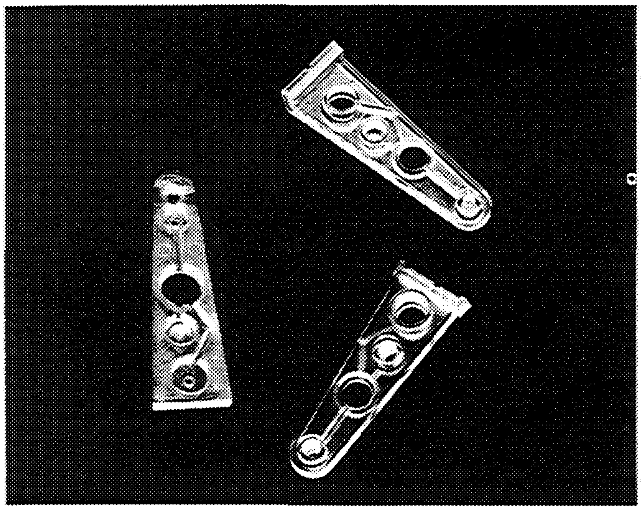

Fig. 6. A medical-optical part in which several functions are combined into a part having optical surfaces.

polymer materials. The possibilities include not only spherical and cylinder lenses, mirrors, prisms, and so on, but extend to screens and complex parts in which the optical element is molded as an integral component of a very complex part (Fig. 6).

What Are The Materials Like?

Optical Properties

If one plots the refractive index and Abbe' values for the most common optical plastics in current use, it becomes obvious immediately that the plastic "glass map" leaves something to be desired. There are virtually no high index polymers, and no polymers having really interesting partial dispersion properties. Crown-flint achromatization is possible using acrylic and styrene, or other material combinations, but individual component powers may be fairly high due to the relatively modest index differences. To make matters more confusing, the optical properties of many materials having attractive optical characteristics are not well documented. Measurement programs now underway should provide much of the missing data, but will be no guarantee of the lot-to-lot consistency as received from the suppliers.

range .85 to about 1.2g/cm^3 making them very attractive where light weight, low moment of inertia, etc. are important considerations. Normal optical glass density ranges from about 2.3g/cm^3 (Schott FK6) to about 6.26g/cm^3 (Schott SF59).

Mechanical Properties

Significant differences in elastic modulus, compressibility, and so on make it important that plastic optical components be mounted in a stress-free manner, and that temperature effects be anticipated so that figure-degrading compressive stresses are avoided. Cemented surfaces are generally to be avoided, since the difference of two large expansion coefficients may be sufficient to produce figure errors. Mounting plastic optics in plastic cells, or molding the cell integral with the part usually sidesteps many of these problems, however. And many of the mechanical properties of optical polymers which at first seem problematical are in fact virtues in environments where impact resistance is essential. In optical gunsights or in projectile optics, where the optics may be forced to survive shock forces amounting to several thousand g's, conventional glass optics are a high risk solution.

Error Budget Distribution

Optical Design

The only justification for employing a special material or process is the opportunity to accomplish something which might not otherwise be possible. But plastic optical materials are sufficiently different from their glass counterparts that the game should be played according to different rules. Early acceptance of this idea is important if the expected cost reductions, performance improvements and so on are to become reality. The difference in procedure begins at the lens design stage of a project. One would normally initiate the optimization process on a system having only spherical optical surfaces. Aspheric figuring might then be added (as a last resort) to a single element if and only if adequate performance were impossible without it. By contrast, the ease with which aspheres may be executed in plastic often permits one to consider all surfaces to be general aspheres initially (provided the lens design program is sufficiently sophisticated to handle them). Weak aspheres which result during optimization may then be made spherical and the system reoptimized, usually with little loss of performance. This approach to optimization frequently results in the development of solution domains very different from conventional all-spherical solutions which are aspherized later in the optimization exercise. Such non-conventional solutions may or may not exhibit unusual constructional and alignment tolerance sensitivity.

Error Distribution

Once the basic optical design has been generated, fabrication and assembly tolerances may be generated in a fairly conventional manner, or further optimization may be performed for the purpose of desensitizing certain critical parameters. The error budget which results should be considerably different for plastic than for glass - a result of the inherent high repeatability of the molding process. A radius parameter, for instance, may be off target as molded, but if the machinery is working correctly, all shots from a single cavity will deviate from the nominal value by an equal amount. A variance of less than a tenth of a percent would not be unusual. By comparison, the production of glass optics is affected by the human decision making process and other factors which result in considerably larger production parameter variations in many cases. In plastic optics, a skewed distribution from the nominal value may be removed from all samples by recalibrating the mold or molding procedure. The same skewness (or lopsided error distribution) in a glass optical system parameter is usually a built-in function of the material, fabrication process, and so on. The use of soft glass may, for example, result in a different axial thickness bias than will harder glasses.

Surface Figure

Ignoring thermal sensitivity for a moment, the inability to control shrinkage, and the resulting surface figure errors, have long prevented plastic from replacing glass outright in many applications. This difficulty is recently yielding to diligent efforts to gain the upper hand. New process control techniques, tooling concepts, molding techniques and materials have made possible plastic optical surfaces which rival all but the best glass elements in modest sizes. The interferograms in Fig. 8 represent several molded plastic optical surfaces in the 1 cm diameter range, having varying amounts of curvature. All indications are that this level of quality will be possible in optics in the 2-3 cm diameter range within the year. Fig. 9 is a collection of interferograms of different samples of the same molded part, attesting to the consistency of current lens molding technology.

Some help is on the way, though. One manufacturer* has expressed their intention to supply an acrylic material of certified purity, and refractive indices will, we are told, be held to within .0002 of nominal, which promises to open new doors to plastic in optical applications. Specifiers of plastic optics would probably be well advised not to hold their breath anticipating the day of plastic apochromats, however.

The relatively large number of thermoplastic materials on the market is encouraging and there is no evidence that a thoroughgoing study of these materials has attempted to identify those having desirable optical properties in the visible region or in the infrared. Such a study would most likely uncover some materials having interesting optical characteristics, thus enlarging the "plastic map." The more common members of the plastic map as it is now known are identified in the diagram in Fig. 7. The diameter of the points plotted is an attempt to denote an uncertainty in the optical properties of the subject material. With the exception of Rohm & Haas V811 Special Acrylic, no claim is made for the accuracy of the data or the magnitude of the observed lot-to-lot variations.

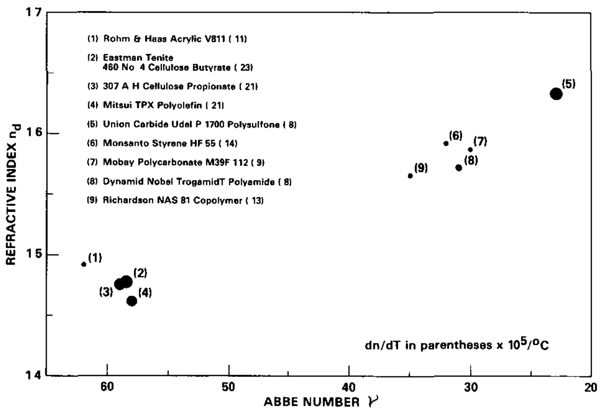

Fig. 7. A few of the points comprising the polymer counterpart to the "glass map."

Note that the thermal coefficient of refractive index (tabulated beside the material identification) is roughly an order of magnitude larger than for most optical glasses, and is negatively signed. This negative sign implies that some interesting athermalization possibilities exist with hybrid (glass-plastic) systems. But in any case, this thermal behavior must be kept in mind where designing a high performance system or a system for use in an unstable thermal environment, especially if no provision is made for refocusing. Fortunately, thermal changes of refractive index appear to have the effect of simply translating the dispersion curve up and down, without producing appreciable changes of shape, which would result in chromatic correction imbalances.

Thermal Properties

Other thermal properties are of equal interest to the optical system designer. Thermal expansion coefficients for most optical grade thermoplastics are roughly an order of magnitude greater than for most optical glasses. The high end of the range is represented by some of the cellulosic materials, around 13×10^{-5}cm/cm/^{0}C; on the low end, the coefficient (α) for certain polycarbonate formulations is about 3×10^{-5}. The corresponding range for the most common optical glasses is about .4 to 1.6×10^{-5}cm/cm/^{0}C.

The thermal conductivity κ (Cal/sec/cm^2/^{0}C/cm) for the optical thermoplastics is in general, quite low. The range is 2.4×10^{-4} (for certain acrylics) to about 6×10^{-4} (for certain polysulfones). For normal optical glasses, the range is $13\text{-}26\times10^{-4}$. Since the deformation introduced in optical element is a function of the ratio of α/κ, one may expect the thermal sensitivity of a plastic optical system to be considerably greater than its counterpart in glass under nonequilibrium conditions.

Continuous service temperature for the optical thermoplastics covers as rather wide range --from about 70^{0}C for some of the styrene formulations to in excess of 250^{0}C for Polysulfones. The mechanical properties of glass and polymer optical materials differ considerably, and should be under constant consideration when comparing the virtues of the two media for a specific application. The density of polymer optical materials covers the

*Rohm & Haas Corporation, Philadelphia, Pa.

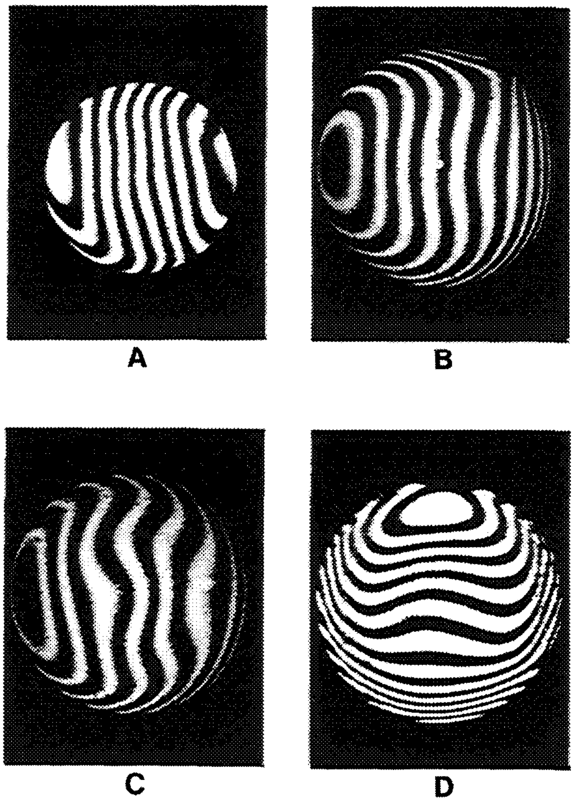

Fig. 8. A collection of interferograms of various polymer optical surfaces in the 1cm diameter range. A-steep convex surface, B-very steep convex surface, C-very steep concave surface, D-mild concave surface.

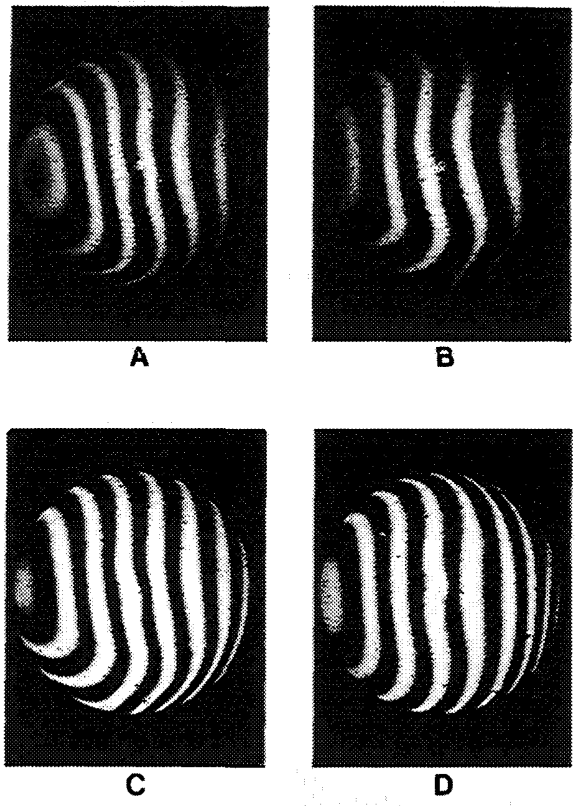

Fig. 9. Interferograms of four samples from same cavity of multi-cavity mold.

Where control of radii and surface figure (irregularity) are concerned, it is worth mentioning that the conventional glass optics specification techniques are of limited value in the plastic optics world. First, inspection of all parts adds greatly to the cost of the parts -- the consistency of the injection molding process requires only spot checking to assure quality in all samples. But more important, the test plate techniques normally applied may inflict cosmetic damage upon plastic optical surfaces. Moreover, if the plastic optical elements are non-circular, or incorporate protruding flanges, spacers, and the like, it may be difficult to achieve contact using a full sized test plate. In general, test plate-oriented specifications of optical surface parameters are not well suited to polymer optics.

Axial thickness may or may not require tight control in an optical element, depending upon the system application. In the glass optics world, control of element thickness to better than ±0.1 mm carries a significant yield or cost penalty. Plastic optical elements, on the other hand, may be manufactured to an axial thickness accuracy of ±.02 mm without much trouble - and tighter control is possible at only a modest cost increase. Control of airspaces may be achieved to the same accuracy level if the lens flanges determine this parameter.

Consistency

Similarly, the centration of a good commercial glass optical element will probably be in the 2-4 arc min range. A typical plastic optical element will have similar centration accuracy. But if need be, the inserts in the mold may be rotated with respect to each other to totally remove centration errors (to the extent that they are measureable). Once this has been done, the improvement in centration carries no cost penalty at all. In fact, the plastic optical elements for a system may be manufactured with features to assure consistent relative orientation. The tabs on the lens in Fig. 10 guarantee the rotational orientation in the cell for all samples.

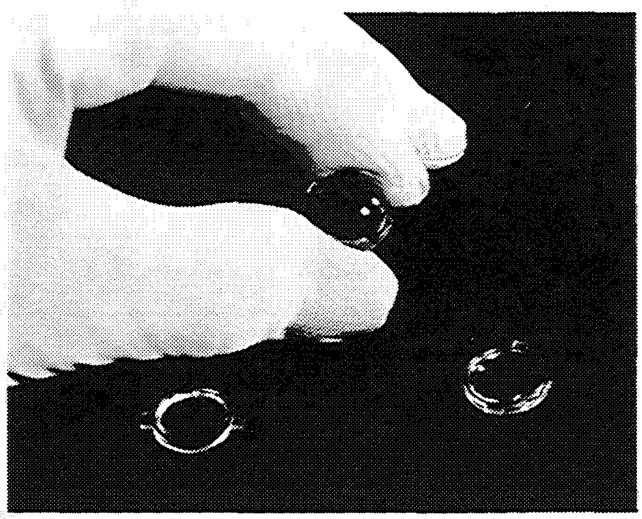

Fig. 10. Parity tabs insure rotational alignment.

In short, the extremely high level of consistency inherent in the injection molding process offers several advantages not found in glass. The master surface, mold dimensions, and process controls can either be calibrated to yield an error envelope much narrower than for glass for most of the constructional parameters, or once the discrepancies from nominal are identified, airspaces may be permanently adjusted (re-optimized in the computer), as one might do a melt balancing operation to compensate for glass melt errors from catalog values.

Optical Effects

The face that very little of the available error budget need be allocated to variations in constructional parameters permits the remainder to be used where it is most needed --in the area of material optical properties. Although thermally induced changes in refractive index and dimensional parameters must certainly be allowed for, it is the basic refractive index values and their spectral dependence which are not well characterized for most polymer optical materials. The relatively modest quantities of these materials sold for optical applications is simply not sufficient inducement for the manufacturers to generate good data, or to provide assurance that the lot variations remain within acceptable limits.

Before selecting polymer materials for an optical application, it is important to be aware of some second order effects which play a role in the performance of the finished part. Most molded parts exhibit evidence of a refractive index gradient at the surface, for example; and small changes in the bulk properties have been observed to be a function of the material heat history. Overpacking of a mold cavity can result in subsequent post anneal relief, resulting in a slight bulge of the optical surfaces and stress birefringence. Most of these and other such effects remain to be accurately quantified, and are in most cases not significant compared to the basic material characteristics. Crystalline polymers, styrene for example, exhibit considerable birefringence (no matter how carefully they are annealed), as do certain copolymers incorporating styrene. Properly molded acrylic parts, on the other hand, are quite isotropic, and exhibit little evidence of strain when examined in the polarimeter. Again, much work remains to be done to quantify this behavior and establish the dependence relationships with molding technique.

But How Do They Look?

Surface Imperfections

There are few production opticians who haven't experienced the satisfaction of producing a part which is dimensionally perfect, with excellent surfaces, only to discover a cosmetic imperfection which is cause for rejection. The disheartening note is, of course, that the optician knows most such cosmetic defects will not degrade performance in the field. Though a discussion of the MIL SPEC requirements is outside the scope of this paper, it should be pointed out that one hundred percent inspection for cosmetic defects can be expected to result in a much larger incremental cost penalty for plastic optics than for glass. Beauty defects which transfer from the mold surfaces will produce samples from that cavity which are either all rejectable or all acceptable. In fact, defects whose size is below a certain threshold often do not transfer at all due to the presence of material surface tension effect. The incidence of sporadic defects on the optical surfaces is sufficiently low that inspection for them is not justified. By comparison, virtually all surface defects in glass are generated sporadically.

Inclusions

Inclusions in the bulk material do occur in plastic optics in several forms. Trapped bubbles almost never occur, however, if the molding process has been optimized to the point that the optical surfaces are of high quality. Likewise, the occurance of black specks (incinerated material) is rare once the process has stabilized enough to produce good surfaces.

Surface Quality

"Haze" due to bulk scatter and surface microroughness, are fairly low in the best polymer materials if properly handled, but are distinctly worse than in good optical glass for other polymer materials. Molding parameters have considerable influence over these effects, however. Fig. 11 is a collection of SEM photos of plastic optical surfaces produced under different molding conditions. Correlation of the production processes and resulting surface scatter is a subject richly deserving serious systematic examination.

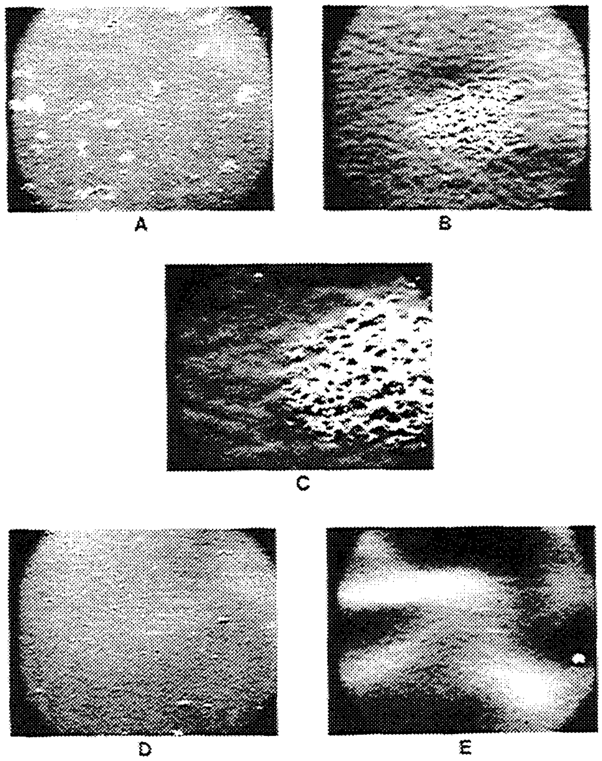

Fig. 11. Scanning electron micrographs: A-surface of cast sheet acrylic at 2000X, B-10,000X, C-20,000X, D-injection molded lens from popular instant camera at 2000X, E-Injection molded lens produced with special controls.

Coatings

It is no secret that the hardness and abrasion resistance of plastics is considerably inferior to that of glass; this may or may not be a functional drawback, depending upon the application. The tendency for plastic optical parts to accumulate electrostatically charged particles, likewise, may be a problem both in the assembly process and in the end use. These properties add to the difficulty associated with cleaning prior to coating; and the low service temperature of some of the materials precludes high temperature baking of a coating for improved adhesion.

Fortunately, several recently developed surface treatments are beginning to promise solutions to most of these problems. Implanation techniques make possible improvement of abrasion properties of most polymer surfaces to the point that they can literally be cleaned with steel wool without significant scratching. These abrasion-resistant surfaces are produced, in some cases, with no visible effect upon optical surface figure. That is, the interferograms of the surfaces are essentially identical before and after coating, (Fig. 12). An additional benefit of such surface treatments is usually a dramatic reduction of the tendency to accumulate charged particles.

Research in the same general vein has produced anti-reflection surface treatments (not quarter wave stacks) which are more impressive in their performance than some of the best high efficiency coatings for glass. In Fig. 13, a spectral response plot of the reflectivity of a typical glass substrate with high efficiency anti-reflection coating is compared to the performance of a treated sample of acrylic plastic. Note that the specular reflection is reduced to about 0.2% over most of the visible spectrum, is a smooth monotonic function, and is free of the steep cut-offs which characterize many multi-layer glass coatings. Current research in the area of polymer optics surface treatment promises to develop within a few months a surface having hardness comparable to glass, little propensity for lint collection, and displaying broadband reflectance comparable with the best H.E.A. coatings - and at a probable cost penalty not too different from that associated with conventional MgF_2 coatings.

Production and Assembly

Cost and performance optimization in plastic optical systems begins with the lens design phase, and is further refined at the drawing board, where every effort should be made to minimize the total number of components by integrating lens elements, spacers, stops, and so on. Careful attention paid to the mechanical integration pays profound benefits in the error budget area. Seemingly equivalent mechanical implementations of the same optical prescription may in fact exhibit very different tolerance stack-up properties. Similarly, careful pre-planning of the assembly techniques (or lack of it) may significantly affect both imagery performance and system yield.

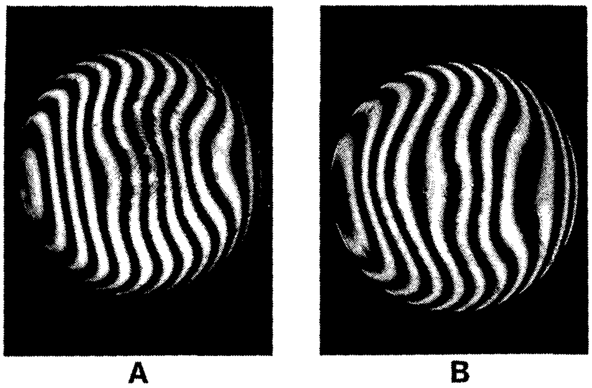

Fig. 12. Interferograms of plastic lens: A-before hard coating, B-after hard coating.

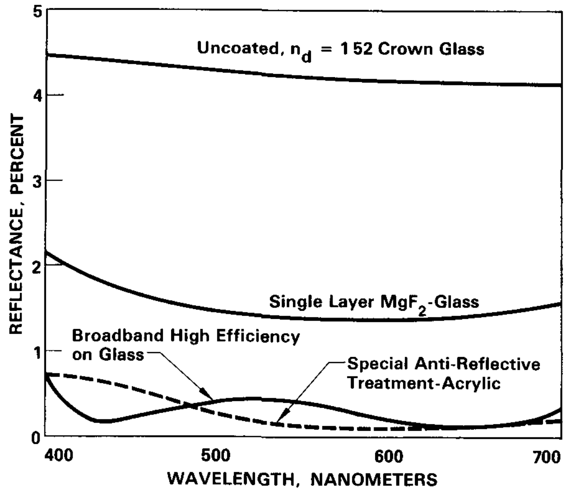

Fig. 13. Spectral response of surfaces treated to reduce specular reflection.

Cost Drivers

The major cost driver in plastic optics is probably the thickness of the optical elements, since the molding cycle duration is roughly proportional to part thickness (for a given optical surface quality level). The lens designer, than, should endeavor to minimize lens element thickness, and reduce the center-to-edge thickness ratio to less than four if possible. Flat, or nearly flat surfaces are to be avoided, since the surface tension effects which are conducive to high accuracy in surfaces of significant spherical power become indeterminate on surfaces having low power, resulting in a need to extend the molding cycle.

The second most significant cost driver is polymer optics is more than likely the quality control requirements. In certain cases, quality assurance costs may actually surpass all other labor costs combined, including molding machine time. These situations are regrettable, since the consistency of the molding process is such that occasional spot sampling is usually sufficient to assure a very high component yield. Q.A. dollars are, in general, more wisely spent to verify performance of complete optical systems, since an occasional reject is not terribly costly. Above all, the specifier of plastic optics should fight off any urge to over-specify. Each and every requirement or constraint applied to the drawings should be the result of some honest soul searching - and should be deleted if it cannot be demonstrated that there is an identifiable influence upon performance.

High Volume Production

The above comments are aimed, of course, at optical systems intended for volume production -- which might be defined in the case of injection molded optics as those whose yearly volume part production costs exceed tooling costs. The largest producers of pocket cameras which incorporate plastic taking lenses have refined the technology to a very high level, at least for moderate quality level optics. Highly automated production lines perform virtually all steps of the production and assembly process with minimal human intervention.

Systems produced in yearly volumes of less than several million cannot justify the cost of highly automated assembly procedures, however. For these systems (the vast majority), some manual assembly and secondary operations will be necessary. The path to be followed will be determined largely by whether the elements require coating or not. In most instances, the long machine cycle time required in molding (usually 1-20 minutes) gives the machine operator time to perform secondary operations, and often assembly procedures. If the optics are to be coated, this time may be put to use to load optical elements into coating fixtures, which may be immediately sealed to reduce contamination due to unnecessary handling operations. Degating, or the hot stamping of apertures onto the elements (Fig. 14) may be done prior to this loading, preferably under a portable laminar flow bench placed over the molding machine.

If the optical elements do not require coating, subassemblies and complete assemblies may be produced at the molding machine to bypass the packing, unpacking and additional handling procedures required in a separate assembly line. Solvent bonding, heat staking, sonic welding, and similar procedures are easily carried out at the molding machine, provided the necessary mechanical parts have been previously produced. Q.A. operations performed on individual parts may be done off line in concert with the inspection of completed assemblies.

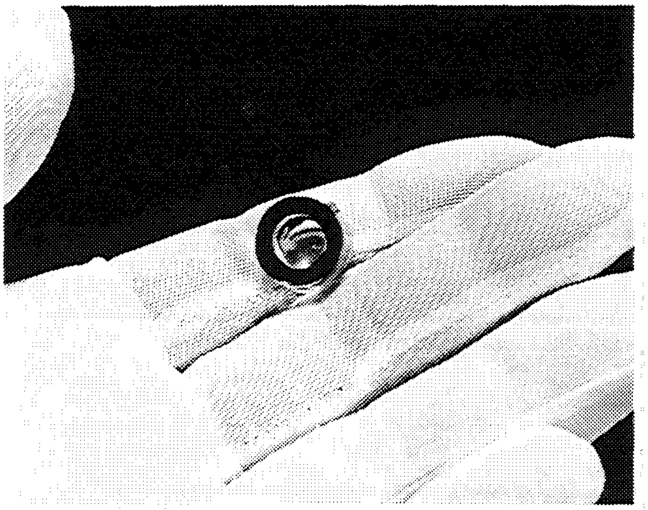

Fig. 14. A lens with an opaque black aperture hot stamped into the surface.

IN CONCLUSION

The discussion above does not constitute an attempt to suggest standard specification procedures for plastic optics. As with glass optics, universal agreement upon even a lexicology for use with plastic optics will probably be years in the making. What has been encouraged is the "zero-based" approach to plastic optics specification writing -- that is, specifying only those requirements and tolerances necessary to usable performance, rather than feeling obliged to provide a specification and tolerance for every conceivable parameter. And while nothing of a specific nature has been said about what to put on a plastic optics part drawing, it has been emphasized that a thorough understanding of characteristics of the materials and associated manufacturing processes will provide most of what one needs to produce an intelligently-conceived plastic optical system description.

Questions from the Floor

Question 1: Any special procedure for polishing the tooling for plastic molds to get good surface finish?

Answer 1: Yes! But the techniques are fairly complex, and beyond the scope of this paper. But 80-50, 60-40, and perhaps 40-20 surfaces are possible in production with rms roughness on the order of 20-30 Angstroms. A great deal more study is required in this area.

Question 2: What is your useable wavelength spectrum?

Answer 2: Presently the useful range extends from about .34 um (certain acrylics) to about 1.2 um (many materials). A few thermoplastic materials transmit selectively beyond 14 um, and there is some hope that a material useful in the 3-5 um region may soon be available.

Question 3: Are there any major problems in moulding polysulfides as compared with acrylics or polycarbonates?

Answer 3: Yes! But the obstacles are not insurmountable.

Question 4: Are there techniques available for bonding plastics? The advantages and disadvantages?

Answer 4: Plastics may be solvent bonded (messy) or joined by ultrasonic welding (neat and clean). Care should be taken to avoid welding near transmitting surfaces in inherently birefringent materials (such as styrene) lest they become more birefringent.

Question 5: Do you have any comments relative to plastic lens drawing callouts as they might relate to glass element drawings? (ie:should there be new callouts for plastics, or is 13830 OK?)

Answer 5: There are a sufficient number of differences in the two (glass/plastic) technologies that a new spec should probably be drafted for polymer optics once the technology has matured. A 3-5 year time frame is anticipated for this maturation.