Optomechanics of Plastic Optical Components

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Ch. 2 from Handbook of Plastic Optics. Second Edition. Stefan Bäumer

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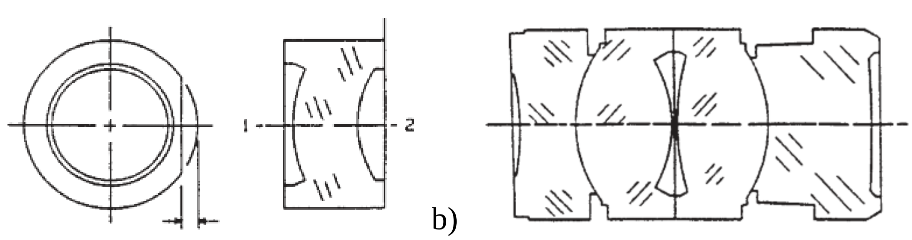
1.1 Introduction

This book chapter describes the main optomechanical aspects that need to be considered when working with optical plastics. In comparison with glasses or metal, optical plastics have very different properties which need to be understood for the optomechanical design, this is particularly important for optical engineers. Plastics offer several advantages over glasses such as capability of low manufacturing cost, freedom with respect design, high shatter resistance, and implementation of cost-saving mounting methods. This also implies challenges, such as higher photoelastic birefringence which requires a careful study of induced stress, higher CTE, sensitivity to stretching, sensitivity to scratches due to low hardness, water absorption, shrinking due to cooling, and discoloration due to ionizing radiation.

1.2 Configuration of Plastic Optical Elements

Plastic optical elements can be used for imaging and non-imaging purposes and they must be treated as opto-mechanical devices that require mounting.

The simplest plastic optical elements are lenses with mounting flanges (Fig.1). Higher stress near the edge of the plastic can cause birefringence and surface irregularities. Consequently, the effective aperture must be at least 1 to 2 mm beyond the full aperture. Also, to allow injection, the minimum thickness edge must vary from 1 to 3 mm.

a)


b)

Figure 1. a) Meniscus lens with gate flat and b) flange spaced lenses

A flange can be also integrated in the lens to protect the surface from damage when it is placed on flat surface. If the flange is used for mounting, then the lens would need a radii that might not comply with the quality of optics. Finally, plastic optical elements can be built to be aligned to each other (Fig.1).

High Functional Integration

Integrating mounting and optical element into a single monolithic assembly decrease the number of optical elements. This decrease cost due to easier assembly and alignment, and also reduce failure rate. Injection-molded optics makes this possible.

Examples: Figure 2a shows a viewfinder assembly integrates two rectangular meniscus lenses, a magnifying lens, and a light-guiding feature to collimate light from a LED. It also incorporates mechanical features including snap hooks and alignment pins. Figure 2b shows an optical module mounted on a flexible circuit

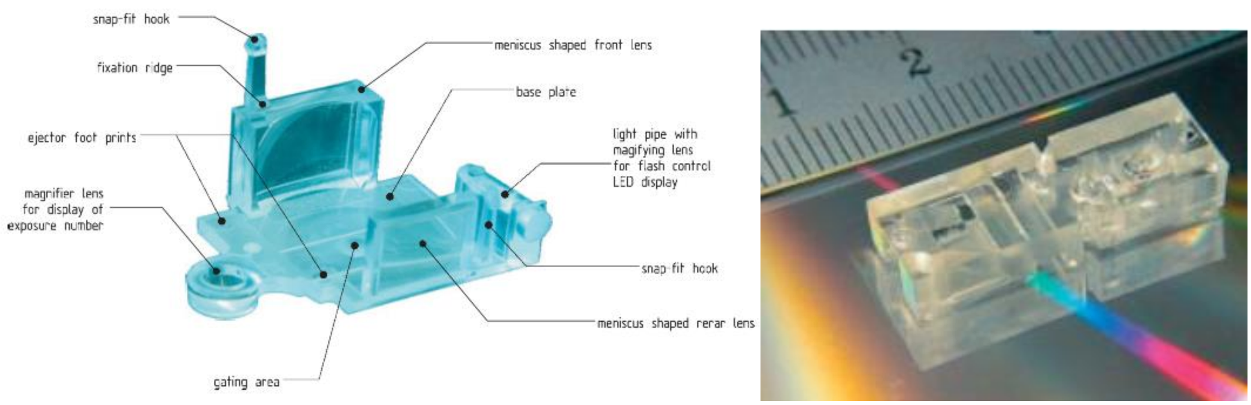


Fig.2 Right: Monolithic camera viewfinder module. Left: small monolithic plastic optical module

1.3 Mounting Plastic Optical Elements

Since the thermal and mechanical properties of plastic are very different from metal, mounting plastic optics requires reinforced plastic materials. There are 3 main types of plastic mounts:

- Clamshell mounts: consist of two half-shells that hold the optics between them (Fig3). Either UV-curing adhesive can be used to bond both parts or C-type expansion rings that also allow for expansion. This type of mounts require a minimum number of parts and are easy to assemble, however there is poor control of centering and tilt.
- Collet cap type lens housing: it is based on slotted collet sleeve in which the lenses are placed. Axially, the lenses lean against the shoulders of the seats and can be fixed with ultrasonically bonded cap.
- Barrel-type lens housing: Similar to the metallic barrel and it provides better accuracy than clamshell mounts. Ring retainers are required. Long mounts and wall-thickness make it difficult to mold barrels with high accuracy.

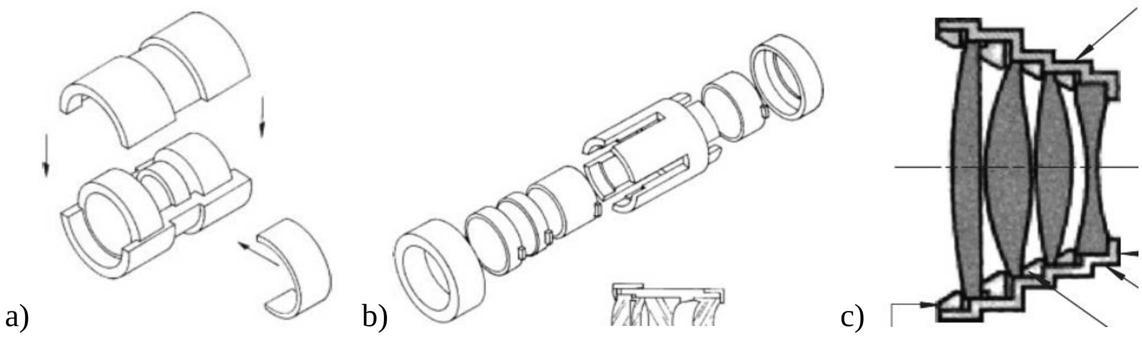


Figure 1. a) Clamshell mounts, b) collet cap-type lens housing, and c) barrel-type lens housing

1.4 Dimensional Stability

It refers to the ability of a material to retain its shape when external conditions are changed, such as temperature, moisture, pressure, or stress.

1.4.1 Structural Stability

This is a basic requirement for all optical systems. The higher the resonant frequency of a component, the stiffer it is. The further the resonant frequency from the excitation frequency, the smaller the oscillation amplitude and hence the smaller the changes. The motion of a vibrating beam is described by:

$$\ddot{x}(t) + \frac{c}{m} \cdot x(t) = 0 \tag{1}$$

where ω_o = sqrt(c/m) and c is the spring constant of the beam, c= EI/l^3. E is the Young's modulus, l the length of the beam, and I the geometrical moment of inertia, which for a beam of width b and height is $I=bh^3/12$. Combining all together and using material density ρ, the resonant frequency reduces to:

$$\omega_0 = \frac{h}{2\sqrt{3l^3}} \cdot \sqrt{\frac{E}{\rho}}. \tag{2}$$

When the deflections of components of equal mass but independent thickness are to be compared the factor ρ/E serves as an appropriate figure of merit. However, when mass of different plastic structures are varied and when keeping deflection constant and independent of thickness leads to the expression ρ^3/E as a figure of merit.

1.4.2 Thermal Stability

This is another important requirement for optical systems. It is related to the coefficient of linear thermal expansion, thermal conductivity, specific heat, thermal diffusivity, and steady-state and transient distortion.

Coefficient of Linear Thermal Expansion: It is the ratio of linear expansion caused by rise in temperature. Typically, the CTE in plastics is 10 times larger than those for glass. Length, area, and volume expansion are:

$$\frac{\Delta L}{L_0} = a \cdot \Delta T; \quad \frac{\Delta A}{A_0} = 2a \cdot \Delta T; \quad \frac{\Delta V}{V_0} = 3a \cdot \Delta T \qquad 3)$$

Thermal Conductivity: Property of the material that indicates how much heat flux moves across a material when a temperature gradient is applied:

$$\Phi_Q = k \cdot \Delta T \qquad 4)$$

where k is the thermal conductivity, $k = \rho * c_p * D$. Here ρ is the density, c_p the specific heat, and D the thermal diffusivity and it is units are W/mk. The thermal conductivity of plastics (0.14 - 0.22 W/mK) is about 3 orders of magnitude smaller than metals and 5 times smaller than glass. Plastic are good thermal insulators.

Specific Heat: The c_p (also called specific heat capacity) it is the amount of heat Q needed to increase the temperature by 1°C:

$$Q = c_p m \Delta T. \qquad 5)$$

For typical polymers, c_p varies from 1.2 to 1.97 kJ/(kgK) which is around twice than metal or glasses. The greater the c_p, the greater the heat needed to change temperature.

Thermal Diffusivity: It is the rate at which a temperature disturbance travels through a material.

$$D = \frac{k}{\rho c_p} \qquad 6)$$

For metals, this is 3 orders of magnitude larger than plastic optical materials while glasses are about 5 times larger. Polycarbonate (PC) has a D of 1.2×10^{-6} m^2/s.

Distortion Coefficients: In steady-state temperature changes, the figure of merit is a/k. Thus, in order to minimize distortion this ratio needs to be small, such as in CR39 plastic. In case of transient thermal changes, the figure of merit is a/D, hence Nylon has low distortion. More ratios are shown in appendix A.

1.4.3 Moisture Expansion

The coefficient of moisture expansion (CME) is defined as the fractional increase in length per unit mass due water absorption. However there are not too many published values on CME. Typical values for PMMA are 0.5%.

1.5 Tolerancing

Tolerancing of plastic systems requires to take into account optomechanical, optical, and production properties. The main aim is to create components that are accurate enough to give the desired performance.

1.5.1 Tolerance Budgeting and Allocation

Tolerance budget can help to find the totally allowable wavefront error (WFE). Most authors agreed that a simple root sum of the squares (RSS) is enough to compute the WFE for a first-order approach. Main errors are due to:

- Residual optical design error, usually expressed as RMS value.
- Fabrication error, due to tooling error of the fabrication method and shrinkage during fabrication process.
- Alignment error, determined by the alignment process and geometry of the system.
- Environment-related error due to realistic conditions. This includes thermal changes that expand material volume creating birefringence, moisture that affects refractive index and dimensions of the material, and finally vibrations that created periodic changes which affect optical performance.

Once the errors are identified as p_i, one must use the wavefront error (sensitivity=$\partial WFE_{tot} /\partial p_i$) to allocate tolerances.

1.5.2 Typical Tolerances and Specifications for Plastic Optics

The boundary conditions are given by the achievable manufacturing tolerances. Reasonable tolerances have to be chosen in order to achieve high performance. In appendix B, typical tolerances for optical plastic are shown.

Moreover, the clear aperture must be less than 90% of the actual aperture. For refractive index, $\pm 10^{-3}$ tolerance can be assumed. Finally, prisms and non-circular elements must have higher tolerances due to fabrication issues.

1.6 Optomechanical Simulation of Plastic Optical Elements

Plastic materials are more sensitive to thermal changes, mechanical stress, or moisture than glass. Some finite element models are being developed to study this.

The material changes should be expressed in terms of polynomials or surface fitting functions. Then, the optical metrics must be evaluated. The main components of the analysis are:

- Thermoelastic analysis. The main property in plastics is the CTE which increase with temperature rise and can have spatial variations.
- Stress Birefringence Analysis. A method to compute it is to calculate the corresponding index ellipsoid map from the spatial stress distribution of the finite element model, using the stress-optical coefficient matrix and the nominal optical properties. Another method includes using Jones matrix to represent birefringence.
- Thermo-optic Analysis. The governing coefficient is dn/dT. A finite element model needs be created and then the OPD due to changes in refractive index can be calculated. Fitting the OPD allow to quantity the WFE.
- Moisture Absorption Analysis. Similarly to previous case, a finite element model can be built using proper boundary conditions.
- Mold Flow Analysis. This allow the simulation of plastic injection which at early stages helps to reduce future errors and problems.

1.7 Conclusions

This chapter makes a fine job of summarizing the physical and thermal properties of optical plastics for opto-mechanical applications. It also mentions typical tolerance values for manufacturing plastics. More details about optical properties are covered in other chapters. Finally, as the author mentions it, more research must be done in applications with high humidity conditions.

References

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Access: http://onlinelibrary.wiley.com/book/10.1002/9783527635443

Appendix A

Thermal properties and figures of merit for plastic optical materials

property			**max. service tempera-ture, air**	**refractive index change per degree**	**coefficient of linear thermal expansion**	**thermal conductivity**	**specific heat**	**thermal diffusivity**	**steady-state distortion coefficient**	**transient distortion coefficient**
symbol			T_{max}	dn/dT	α	k	c_p	D	α/k	α/D
unit			°C	10^{-6}/K	10^{-6}/K	W/(m K)	W s/(kg K)	10^{-6} m²/s	mm/W	s/(m² K)
preferred			large	small	small	large	large	large	small	small
material	abbrev.	trade name								
cyclic olefin copolymer	COC	Topas	130	–104.3	63	0.16			394	
cycloolefin polymer	COP	Zeonex, Zeonor	123	–126	67					
polycarbonate	PC	Makrolon, Lexan	130	–143	70	0.2	1.2	0.14	348	500
poly(methyl methacrylate)	PMMA	Plexiglas	86	–85	72	0.21	1.4	0.13	344	573
polystyrene	PS		80	–120	70	0.17			411	
allyl diglycol carbonate		CR39	100		120	0.55	1.45	0.36	218	332
poly(styrene-co-acrylonitrile)	SAN		77		65	0.14	1.7	0.07	464	916
poly(styrene-co-methacrylate)	NAS		95	–140	65					
poly(4-methyl-1-pentene)	PMP	TPX	180		117	0.167	1.97	0.1	700	1150
amorphous nylon		Grilamid TR90	118		9	0.16	1.8	0.08	56	108
poly(ether sulfone)	PSU	Udel	160		56	0.26				
poly(ether imide)	PEI	Ultem	210		55.8	0.22				
borCrown glass		BK7		138	7.1		858	0.5	6.4	13.7
aluminum		AlMg1Si	580		22.5	167	896	69	0.13	0.33

Appendix B

Typical tolerances and specifications for injection molded plastic optical parts

	low cost	commercial	state of the art	extremely tight
focal length (%)	±3–5	±2–3	±0.5–1	±0.5
radius of curvature (%)	±3–5	±2–3	±0.8–1.5	±0.3
power (fringes)	10–6	5–2	1–0.5	
irregularity (fringes/10 mm)	2.4–4	0.8–2.4	0.8–1.2	
scratch/dig	80/50	60/40	40/20	
centration	±3′	±2′	±1′	
center thickness (mm)	±0.1	±0.05	±0.01	±0.015
flange diameter (mm)	±0.1	±0.05	±0.005/∅10	±0.015
radial displacement (mm)	0.1	0.05	0.02	
repeatability (%)	1–2	0.5–1	0.3–0.5	
diameter/thickness ratio	2:1	3:1	5:1	
bubbles and inclusions (ISO 10110–3)		1 × 0.16	1 × 0.10	1 × 0.06
surface imperfections (ISO 10110–6)		2 × 0.10	2 × 0.06	2 × 0.04
surface roughness (nm_{RMS})	10	5	2	