Polymer optics

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Introduction:

Nowadays polymer optics has been widely used in different fields. Compared with the glass material, the polymer has lower density and much cheaper price although it also has some obvious limitations. Paul Tolley's paper gives a good review of polymer optics. In the paper, the development of the polymer optics is first introduced. Then the optical and mechanical properties of different polymer material are discussed in detail. This paper focuses on the comparison of different fabrication methods of polymer materials in details. This paper would help the engineers to understand the fabrication limitations of the material and to balance the advantages and disadvantages of the polymer before using it for their systems. Compared with other reference papers, this paper gives a good introduction of the polymer material and it pays special attention on the high refraction diamond turning methods.

This Synopsis is mainly based on the Paul Tolley's conference paper "Pushing the polymer envelope" at the SPIE 2005 Optics& Photonics conference. Besides this paper, some other papers are referred in the Synopsis.

Material development

The author first talks about the plastic material history from which we might see the future of the polymer industry. The entire industry of polymer material has about 150 years' old history. In early years, because of the lack of high precision fabrication method, the plastic lenses were relegated to toys, low accuracy eye pieces and cheap cameras. The first acrylic optical lenses are made for ophthalmic applications in 1936. Around 1940 acrylic is widely used for aircraft canopies and light window applications. Later in 1960 the PMMA and polystyrene are used in the low cost fixed focus cameras by Kodak. In early 1980s, optical grade polycarbonate is widely used for ophthalmic lenses, safety glasses and firemen's shields. With the continued improvement in material fabrication and manufacturing method, the advances in polymer materials experiences breakthrough in the 1990s. The development of optical grade polyetherimides, polyethersulfones and cyclic olefins greatly expands the application of the polymer materials. These plastic exhibit higher transmission in the near IR and can withstand high operating temperature.

Optical properties

The author talked about the properties of common polymers. Here I give a review on the advantages of different polymer material which may help people to select right material for their application. Compared with the other materials, such as glass material, the plastic has much smaller density but also shows excellent optical property. Acrylic and polystyrene are two most popular materials since they have long history and are easy to fabrication. One of the distinguishing features of acrylic is its high transmission about 92~95%. Acrylic and polystyrene can be used together as a doublet for a lens system, since acrylic has a high Abbe number and polystyrene has a low Abbe number. Polycarbonate has high impact resistance and temperature resistance. It is becoming more common in housewares as well as laboratories and in industry. Polyetherimide has highest refraction index and highest working temperature compared with other polymer material. It exhibits high transmission in the near IR region. Cyclic Olefin Polymer (COP) is a type of new material. It has extremely low water absorption and also has low dN/dT, which make it a stable material in different environment. Besides the properties listed in the table, birefringence is also an important issue for plastic material. It has terrible effects on the polarization sensitive systems. The birefringence will change the polarization of the light unpredictably. This effect is process driven, and it is generally a problem for the plastic component using the molding method. Materials with higher flow rates are less susceptible. But for the components are manufactured using diamond turning method birefringence is usually not an issue.

Table I. optical properties of different polymer material

	Unit	Acrylic	Polystyrene	Polyetherimide	Poly-carbonate	Methyl-pentene	ABS	Cyclic Olefin Polymer	Nylon	NAS	SAN
n_F (486.1 nm)		1.497	1.604	1.689	1.593	1.473		1.537		1.575	1.578
n_d (589 nm)		1.491	1.590	1.682	1.586	1.467	1.538	1.530	1.535	1.533–1.567	1.567–1.571
n_c (656.3 nm)		1.489	1.585	1.653	1.580	1.464		1.527		1.558	1.563
Abbe Value V_d		57.2	30.8	18.94	34	51.9		55.8		35	37.8
Transmission	%[1]	92–95	87–92	82	85–91	90	79–90.6[2]	90–92	88	90	88
Max Service Temp.	°F	161	180	338	255			253	179.6	199.4	174–190
	°C	72	82	170	124			123	82	93	79–88
Water Absorption	%[3]	0.3	0.2	0.25	0.15			<0.01	3.3	0.15	0.2–0.35
Haze	%	1–2	2–3		1–3	5	12	1–2	7	3	3
dN/dT	x10^{-5}/°C	–8.5	–12.0		–11.8–14.3			–8.0		–14.0	–11.0
Color/Tint		Water clear	Water clear	Amber	Water clear	Slight yellow		Water clear		Water clear	Water clear

Manufacturing process

Manufacture is very important issue, since not all the polymer materials are easy to fabricate. Currently there are two popular methods for the fabrication of polymer elements: molding and diamond turning method.

a. Molding

Molding method is an old fabrication method but a very common method for mass production at low costs. It would be expensive and time consuming to setup the mold for fabrication, but it is generally cheap and fast to mold the plastic element after the setup. It would be best way for the high volume production.

b. Single point diamond turning (SPDT)

Compared with the molding method, SPDT method is more accurate. It allows for highly accurate surface geometry generation, including toric, aspheres and diffractives. From the practical view, SPDT reduces the leadtime of fabrication for the elements and allowing for multiple proof-of-concept runs at low cost. The start-up expense of a mold and mold processing can cost $20K on average, but SPDT offers the possibility of a proof-of concept solution completed within a month for less than $5K. Based on the comparison of the costs and leadtime, the author believes that SPDT would be a much better approach for the prototyping.

But the author also points out that not all the materials are suitable for SPDT. Only PMMA, polystyrene, polycarbonate and COP are appropriate, while polyetherimide (PEI) and polyethersulfone(PES) that can be used in the high refraction, high thermal applications can not be fabricated since they are too brittle.

c. High refraction diamond turning (HRDT)

As its name indicates, HRDT method is mainly for the fabrication of the material with high refraction index. PEI and PES are two types of polymer materials that have relative high refraction index. Because of the material properties mentioned earlier, both materials are promising candidates for IR applications, and they also can be used in the fiber couplers since they have high refraction index.

The author explained a lot why the HRDT method is such an important fabrication method. He also explained roughly the HRDT process. The basic idea is that they developed a custom annealing process that was absolutely repeatable for a given design based upon material lens geometry, lens thickness and mass. The author compared the results of RMS roughness of the surface using SPDT and HRDT methods. It shows that HRDT can successfully achieve 60A RMS roughness while SPDT machining can only achieve 390A RMS roughness.

The author emphasized that in the HRDT method it is critical to understand the desired geometry and to systematically adjust both the level of annealing and all factors of standard diamond turning process according to that geometry.

The application of polymer

The polymer materials have wide applications. These applications do more than replace glass components with polymer ones; they provide new solutions to previously intractable problems, such as one-time use without expensive sterilization, or reusing the same components in very different packaging. These applications include the follows:

- Biomedicine, including blood assay diagnostics and disposable surgical and treatment devices. Satisfying one time use requirements cost-effectively virtually requires plastic optics.
- Biometrics, including three-dimensional facial imaging, readers of palm- and fingerprints and retinal scanners. In this application, plastic optics solutions combine design versatility with high repeatability and low cost.
- Defense and homeland security, including guided weapons, head-up displays and identification and tracking devices. For example, Raytheon's paveway laser-guided bomb, uses plastics lenses to acquire target because of their relatively low weight and a cost five times lower than their predecessors.
- Illumination systems. Plastic is preferred since it has low weight and high transmission in visible to the near-IR wavelength.

Summary:

Tolley's paper gives a brief review on the polymer optics. This paper would help engineers to select the proper material for their prototyping. Although the information in this paper is very general, we can get some practical ideas on the polymer material. For example, last semester I designed a projection lens using plastic for my research, but I did not realize that I chose the material that is not good for the

SPDT method until I read this paper. This paper also talked a lot HRDT method which is the trademarks of the author's company. This method extends the application of the diamond turning method.

Reference:

1. Paul Tolley, "Pushing the polymer envelope", SPIE 2005 Optics& Photonics conference, Volume 5872, pp. 102-113 (2005).
2. Paul Tolley, "Polymer optics gain respect", Photonics spectra, October 2003.
3. J. Burge, Class notes of Optics 521, College of Optical Sciences, University of Arizona, Fall 2007