Practical Plastic Optics

Practical Optics Seminar
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Overview

- Plastic Optics?
- Optical plastics
- Basics of injection molding
- Design guidelines
- Tolerances
- Coatings
- Design Examples
- Optomechanical design
- Prototyping
- Testing
- References
Plastic Optics - Potential Advantages

• Cost
• Production volume – can make large quantities with high quality and repeatability
• Integral features – can have mounting features or multifunction parts
• Reduced weight
• Aspheric and diffractive surfaces
Plastic Optics - Potential Disadvantages

- Lower service temperature than glass
- Higher dn/dt and CTE
- Environmental susceptibility
- Birefringence
- Limited material selection
## Properties of Optical Polymers

<table>
<thead>
<tr>
<th>Material</th>
<th>PMMA</th>
<th>P-STYR</th>
<th>P-CARB</th>
<th>SAN</th>
<th>NAS</th>
<th>COC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typ Mfg</td>
<td>AtoHaas</td>
<td>Monsanto</td>
<td>GE</td>
<td>Mon</td>
<td>Richardson</td>
<td>Topas</td>
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<tr>
<td>'Glass Code'</td>
<td>492.572</td>
<td>590.309</td>
<td>585.299</td>
<td>567.348</td>
<td>564.334</td>
<td>533.567</td>
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<tr>
<td>Spec Grav</td>
<td>1.18</td>
<td>1.05</td>
<td>1.25</td>
<td>1.07</td>
<td>1.09</td>
<td>1.02</td>
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<tr>
<td>Serv Temp (C)</td>
<td>85</td>
<td>75</td>
<td>120</td>
<td>80</td>
<td>80</td>
<td>150</td>
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<tr>
<td>Exp Coeff *</td>
<td>60</td>
<td>50</td>
<td>68</td>
<td>50</td>
<td>58</td>
<td>60</td>
</tr>
<tr>
<td>dn/dt *</td>
<td>-105</td>
<td>-140</td>
<td>-107</td>
<td>-110</td>
<td>-115</td>
<td>-101</td>
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<tr>
<td>Birefringence **</td>
<td>4</td>
<td>10</td>
<td>7</td>
<td>5</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>% H₂O absorp †</td>
<td>0.30</td>
<td>0.10</td>
<td>0.20</td>
<td>0.28</td>
<td>0.15</td>
<td>0.01</td>
</tr>
<tr>
<td>Trans (vis avg) ‡</td>
<td>0.92</td>
<td>0.90</td>
<td>0.88</td>
<td>0.90</td>
<td>0.90</td>
<td>0.92</td>
</tr>
<tr>
<td>Haze (%) ‡</td>
<td>2.0</td>
<td>3.0</td>
<td>2.0</td>
<td>1.5</td>
<td>1.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Rel Cost</td>
<td>$$</td>
<td>$</td>
<td>$$</td>
<td>$</td>
<td>$</td>
<td>$$$</td>
</tr>
<tr>
<td>Attributes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>SPDT</td>
<td>EXCEL</td>
<td>FAIR</td>
<td>POOR</td>
<td>EXCEL</td>
<td>EXCEL</td>
<td>GOOD</td>
</tr>
<tr>
<td>COATING</td>
<td>GOOD</td>
<td>GOOD</td>
<td>GOOD</td>
<td>GOOD</td>
<td>GOOD</td>
<td>GOOD</td>
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</tbody>
</table>

- * X10⁻⁶ C
- ** Relative 0 to 10
- † 24 hr immersion
- ‡ 3mm thk
Manufacturing Methods

- Casting
- Embossing
- Machining
- Injection molding
Schematic of Injection Molding Machine
Production Volumes

• Simple math, with scaling assumptions
• 30 days = 43200 minutes
• Number of cavities = 8
• Up time percentage = 90%
• Cycle time = 1.5 minutes
• Monthly volume = 207,360 parts
Injection Molding Design Guidelines

• If possible:
  – Avoid plano and weakly curved surfaces
    • Try moderate radius < 50 mm
  – Avoid strong biconcave elements
    • Maintain adequate center thickness for proper flow
  – Maintain adequate edge thickness for injection
    • Allows proper flow, avoid jetting
  – Reduce unnecessary thickness
Design Guidelines (cont.)

• If possible:
  – Have at least 1 mm outside clear aperture
    • Leaves room for edge break
  – Place diffractives on relatively weak power surfaces
    • Keep eye on minimum step size
    • Minimize angle variation
    • Look at effect of other diffractive orders
Design Guidelines (cont.)

• If possible:
  – Minimize aspheric terms, eliminate unnecessary aspheres
  – Think about stray light during design
  – Think about opto-mechanical design
  – Consider coatings/filter placement during design
  – Round corners on square/rectangular parts
USE A WEAKLY CURVED SURFACE

DO NOT USE PLANO OR WEAK SURFACE RADIUS
(SURFACE WILL 'SINK')

A DIFFRACTIVE HERE CAN HAVE POOR DIFFRACTION EFFICIENCY

CT TOO THIN AND ET TOO THICK
MELT WILL 'RACETRACK'

PREFERRED CT AND ET RATIO
GOOD MELT FLOW

KEEP MODEST RADIUS HERE

THE TWO LENSES ON THE LEFT HAVE SAME POWER
THE TWO LENSES ON THE RIGHT HAVE SAME POWER
Injection Molded Plastic Tolerances

<table>
<thead>
<tr>
<th></th>
<th>Commercial</th>
<th>Precision</th>
<th>State-of-the-Art</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>± 5%</td>
<td>± 2%</td>
<td>± 0.5%</td>
</tr>
<tr>
<td>EFL</td>
<td>± 5%</td>
<td>± 2%</td>
<td>± 1.0%</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>±0.13</td>
<td>±0.05</td>
<td>±0.020</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>±0.13</td>
<td>±0.05</td>
<td>±0.020</td>
</tr>
<tr>
<td>Surface Figure</td>
<td>&lt;10f (5λ)</td>
<td>&lt;6f (3λ)</td>
<td>&lt;2f (1λ)</td>
</tr>
<tr>
<td>Surface Irreg</td>
<td>&lt; 5f (2.5λ)</td>
<td>&lt;3f (1.5λ)</td>
<td>&lt;1f (0.5λ)</td>
</tr>
<tr>
<td>Surface RMS err</td>
<td>&lt;100A</td>
<td>&lt;50A</td>
<td>&lt;20A</td>
</tr>
<tr>
<td>Surface S/D qual</td>
<td>80/50</td>
<td>60/40</td>
<td>40/20</td>
</tr>
<tr>
<td>Wedge (TIR)</td>
<td>&lt;0.025 mm</td>
<td>&lt;0.015 mm</td>
<td>&lt;0.010 mm</td>
</tr>
<tr>
<td>Radial Displ</td>
<td>&lt;0.100 mm</td>
<td>&lt;0.050 mm</td>
<td>&lt;0.020 mm</td>
</tr>
<tr>
<td>Aspect Ratio *</td>
<td>&lt;8:1</td>
<td>&lt;6:1</td>
<td>&lt;4:1</td>
</tr>
<tr>
<td>Repeatability**</td>
<td>&lt;2%</td>
<td>&lt;1%</td>
<td>&lt;0.5%</td>
</tr>
<tr>
<td>DOE depth</td>
<td>---</td>
<td>±0.25 um</td>
<td>±0.10 um</td>
</tr>
<tr>
<td>DOE min groove</td>
<td>---</td>
<td>25 um</td>
<td>10 um</td>
</tr>
</tbody>
</table>

* diameter/thickness ratio  
** part to part in one cavity

• NOTES: Above tolerances are for 10 to 25 mm diameter elements. Surface figure and irregularity expressed in fringes (waves) per inch of diameter.
Coatings

• AR coatings
  – More elements, more reflection loss
  – Typically use multilayer for broadband
  – Most materials can be coated
  – Coatings continue to improve
  – Usually best to have coated at same place that is molding
Plastic Optics Designs

• Often highly constrained
• Tradeoffs
  – Cost
  – Performance
  – Manufacturability/yield
  – Height/weight/volume
  – Specific optical characteristics
    • Chief ray angle
    • Distortion
    • Flare
SEVEN ASPHERIC SURFACES
LONG OAL DISTANCE

6 MM EFL, F/2 WEBCAM OBJECTIVE NO 1  Scale: 7.50  23-Apr-01
LONGITUDINAL SPHERICAL ABER.

FOCUS (MILLIMETERS)

-1.00 -0.75 -0.50 -0.25

0.0 0.25 0.50 0.75 1.00

ASTIGMATIC FIELD CURVES

IMG HT

3.00

2.25

1.50

0.75

FOCUS (MILLIMETERS)

-1.00 -0.75 -0.50 -0.25

0.0 0.25 0.50 0.75 1.00

DISTORTION

IMG HT

3.00

2.25

1.50

0.75

% DISTORTION

-5.0 -2.5 0.0 2.5 5.0

6 MM EFL, F/2 WEBCAM OBJECTIVE NO 1 23-Apr-01
6 MM EFL, F/2 WEBCAM
OBJECTIVE NO 1
DIFFRACTION MTF

23-Apr-01

DIFFRACTION LIMIT
AXIS

WAVELENGTH WEIGHT

650.0 NM 1
600.0 NM 2
550.0 NM 2
500.0 NM 2
450.0 NM 1

DEFOCUSING 0.00000

FULL SPECTRAL BAND
FIELD HEIGHTS ARE AXIAL, TOP, SIDE, CORNER
21

6 MM EFL, F/2 WEBCAM OBJECTIVE NO 2

Scale: 7.50
23-Apr-01
LONGITUDINAL SPHERICAL ABER.

FOCUS (MILLIMETERS)

ASTIGMATIC FIELD CURVES

IMG HT

DISTORTION

IMG HT

6 MM EFL, F/2 WEBCAM OBJECTIVE NO 2

23-Apr-01
6 MM EFL, F/2 WEBCAM
OBJECTIVE NO 2
DIFFRACTION MTF
24-Apr-01

DIFFRACTION LIMIT

WAVELENGTH  WEIGHT
650.0 NM  1
600.0 NM  1
550.0 NM  1
500.0 NM  1
450.0 NM  1

DEFOCUSING 0.00000
6 MM EFL, F/2 WEBCAM
OBJECTIVE NO 2

Radius for surface 7

Phase for HCO

65 WAVES POWER
24 MICRON MINIMUM GROOVE SPACE

23-Apr-01
DIFFRACTIVE SURFACE

IR-BLOCK FILTER

DETECTOR WINDOW

PMMA

THREE ASPHERIC SURFACES
LONGITUDINAL SPHERICAL ABER.

FOCUS (MILLIMETERS)

-0.10 -0.05 0.0 0.05 0.10

ASTIGMATIC FIELD CURVES

FOCUS (MILLIMETERS)

-0.10 -0.05 0.0 0.05 0.10

DISTORTION

IMG HT

-5.0 -2.5 0.0 2.5 5.0

6.0 MM, F/2.5 WEBCAM OBJECTIVE NO 3

24-Apr-01
6.0 MM, F/2.5 WEBCAM
OBJECTIVE NO 3
DIFFRACTION MTF

24-Apr-01

DIFFRACTION LIMIT

<table>
<thead>
<tr>
<th>WAVELENGTH</th>
<th>WEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>650.0 NM</td>
<td>1</td>
</tr>
<tr>
<td>600.0 NM</td>
<td>1</td>
</tr>
<tr>
<td>550.0 NM</td>
<td>1</td>
</tr>
<tr>
<td>500.0 NM</td>
<td>1</td>
</tr>
<tr>
<td>450.0 NM</td>
<td>1</td>
</tr>
</tbody>
</table>

DEFOCUSING 0.00000

SPATIAL FREQUENCY (CYCLES/MM)
6.0 MM, F/2.5 WEBCAM
OBJECTIVE NO 3

24-Apr-01

Phase for HCO

60 WAVES POWER
17 MICRON MINIMUM GROOVE

Radius for surface 5
NOTES: UNLESS OTHERWISE SPECIFIED

10. GATE LOCATION
11. CAVITY ID: SEQUENTIAL PROTRUDING FEATURES
12. FILLET RADIUS: .05 MAX.
13. DRAFT PERMITTED WITHIN SPECIFIED TOLERANCE.
14. PART DATA BASE TAKES PRECEDENCE OVER DRAWING.
15. THIS ELEMENT IS AN INJECTION-MOLDED COMPONENT USED IN AN OBJECTIVE ASSEMBLY. DIMENSIONS FOR RADIUS, CA, & CT ARE MM. PMH/IRB TOLERANCES ARE FRINGES AT 633NM.
16. OAL1 IS THE THEORETICAL OPTIC AXIS OF THE FIRST OPTIC SURFACE.
17. OAL2 IS THE THEORETICAL OPTIC AXIS OF THE SECOND OPTIC SURFACE.
18. DRAFT ON O.D. OF PART IS 1/2°.
19. USE OF MOLD RELEASE IS NOT PERMITTED.
20. GATE VESTIGE NOT TO EXCEED PART O.D.
21. MATERIAL: OPTICAL GRADE ATOMHAS PLEXIGLAS VB25-100 OR EQUIVALENT.
   Ng=1.4910 +/- 0.001
   IV(F-C)=57.2 +/- 0.1
22. SURFACE FINISH EXCLUDES OPTICAL SURFACES. SPI #<3
   CVH<2
   5. S1 HAS AN ASPHERIC PROFILE GIVEN BY: Z(H)=------------------- \[\frac{A4H^4+B4H^6+C4H^8}{1+\sqrt{1-(1+\kappa)CVH^2H^2}}\] 0.5
   WHERE: H: RADIAL DISTANCE FROM S1 VERTEX IN MM
   CV=1, \kappa=-1.065808, A=0.000000, B=0.000000, C=0.000000, R=7.00126MM
   CVH<2
   4. S2 HAS AN ASPHERIC PROFILE GIVEN BY: Z(H)=------------------- \[\frac{A4H^4+B4H^6+C4H^8}{1+\sqrt{1-(1+\kappa)CVH^2H^2}}\] 0.5
   WHERE: H: RADIAL DISTANCE FROM S2 VERTEX IN MM
   CV=1, \kappa=-1.747370, A=0.000000, B=0.000000, C=0.000000, R=4.74184MM
3. S1 AND S2 SURFACE FINISH <99 ANGSTROM RMS ROUGHNESS
   AND 60-40 OR EQUIVALENT OPTICAL QUALITY.
4. FEATURES IDENTIFIED AS & ARE CRITICAL CHARACTERISTICS.
5. FEATURES IDENTIFIED AS @ ARE SPEC ITEMS.
Prototyping

• Due to cost and time for production molds, typically prototype design first

• Methods
  – Diamond Turning
  – “Stock” Molds
  – Single Cavity Mold
Common Testing

• Surfaces – Profiler or interferometer (may require null lens)

• Mechanical – CMM, indicators, etc.

• System – MTF bench, resolution test

• Stray light – Collimator, light bulb, sun
References

• Handbook of Plastic Optics – Baumer (Ed.), published by Wiley

• Handbook of Plastic Optics – USPL

• OSA Handbook of Optics – Vol. 2, Chapter by Lytle