SUBSTRATE CO-MOLDING OF MICRO AND MESO OPTICS

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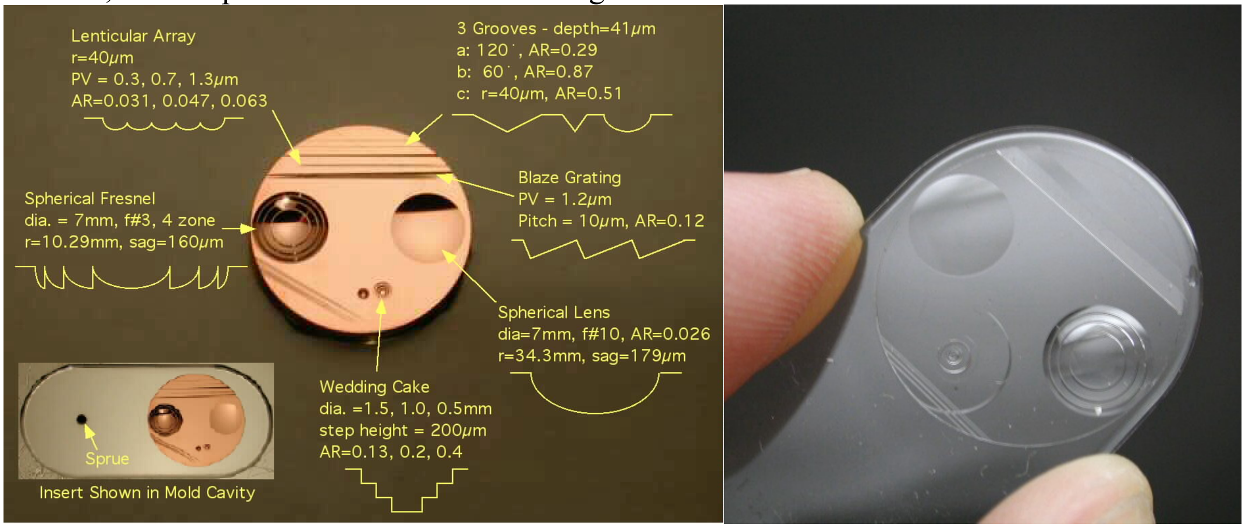
INTRODUCTION

The objectives of this research were to develop a novel process of replicating thermally stable precision optics by injection molding the optical features directly onto glass substrates. The development of this technology will promote the use of optical communication in many settings including inside computers by creating inexpensive optics that can be co-molded directly onto printed circuit boards or silicon semi-conductors. Injection molded polymer optics offer high production volumes, but suffer from their high coefficient of thermal expansion and their hygroscopic nature. The investigation includes methods of promoting the adhesion of polymer to substrates and the performance of the co-molded optics in varying environments.

EXPERIMENTAL APPARATUS

To address the research goals, a series of experiments have been carried out on a laboratory-scale Nissei hydraulic injection molding machine at the Precision Engineering Center. The small size of the machine is necessary for the replication of meso optics with thickness below 350 micrometers and lens area less than1800 sq mm. The mold inserts are diamond turned and include spherical lenses, diffraction gratings, and Fresnel lenses. Features in the mold have step heights from 80nm to 170µm and include both smooth and sharp edges. The mold insert, optical features, and a replicated lens are shown in Figure 1.



(a) (b)

Figure 1. Injection Mold Insert (a) and a Replicated Acrylic Lens (b) Showing Optical Features

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The molding substrates included soda lime, borosilicate, and fused silica (quartz) microscope slides. The mold system was adapted to hold, accurately locate, and eject the substrates from the mold. Additionally, the mold system was designed so that lenses could be molded with or without the substrate. This design allowed the machine to be brought to equilibrium by molding all-polymer lenses before substrate co-molding began.

EXPERIMENTAL PROCEDURE

The first step in co-molding was to determine the molding process factors that had the greatest effect on the replication of meso and micro optics. A portion of this factors and effects test was reported at the ASPE 2001 Annual Meeting, but lens transmission tests had not been completed at that time. The factors and effects test included a reduced factorial, screening design of experiment that included 32 different sets of test conditions to determine the effects of 9 molding factors (process parameters). The tests required the molding of over 3000 lenses and the measurement of 100 of those lenses. The optical geometry of the replicated lenses was measured through interferometry, stylus profilometry, and atomic force microscopy.

Power transmission was chosen as the metric for comparison of lens transmission capabilities. This measurement is used in fiber optics to determine the ability of a lens to focus light into the end of a fiber optic. The power of an open light beam is measured and then compared to the power of light focused into the fiber. The result is reported as a percentage of the open beam power. Typical causes of power loss include optical astigmatisms that prevent the light from focusing at a single point, reflection off of lens surfaces, and absorption of light in the polymer material. For this research, a semi-conductor power meter was used in conjunction with 632.8nm light.

The second step in the co-molding research was to experiment with different substrates, cleaning methods, surface chemistry modifiers, and injection molding process parameters. The substrates used had a thickness of 1mm and the co-molded polymer optic was 150μm thick. The substrate materials were soda lime, borosilicate, and fused silica (quartz) glass. Cleaning methods included common solvents, glass cleaners, and the JTB1-1-1 method that is commonly used to clean silicon wafers. Immediately after cleaning, the substrates were either used for co-molding, or they were coated with a organofunctional silane solution to modify the inorganic surface of the substrate so that it would more easily bond with the organic polymer lens. Many molding factors were adjusted to promote adhesion including the injection pressure and temperature, mold temperature, screw rotation speed and cooling time in the mold.

RESULTS

The results of the factors and effects test revealed the factors having the greatest effect on the replication accuracy of the optical features. The factors with the greatest effect were found to be screw rotation speed and mold temperature. Other factors having statistically significant effects, though of a much smaller magnitude, were mold position, nozzle temperature, injection speed, hold time, and hold pressure. The magnitude of the effects due to the factors varied between the different optical features but the positive or negative influence was common to all features. For example, a higher mold temperature greatly increased the replication fidelity of the blaze diffraction grating. While the higher mold temperature did not affect the other features in nearly the magnitude of its effect on the diffraction grating, all of the other features had better or equal replication at the higher mold temperature tested. This agreement was not intuitive, as the features varied widely in size and shape. Table 1 shows the minimum error in each feature from the factors used in the design of experiment. It is expected that these errors could be even lower with further work refining the values of the factors, but from the 32 tested combinations of factors, the smallest error values are presented.

Table 1. Minimum Error Values for Geometric Measurements from the Screening Experiment

Feature	**Measurement**	**Part #1 Error (nm)**	**Part #2 Error (nm)**	**Part #3 Error (nm)**	**Average Measured Error (nm)**	**Standard Deviation of Measurements (nm)**
Spherical Lens	Astigmatism	773.9	572.7	488.5	611.7	146.6
	Coma	150.0	144.9	145.5	146.8	2.76
	Spherical Aberration	118.3	126.6	98.1	114.3	14.7
	PV Sphere Residual	836	651	585	690.7	130
	RMS Sphere Residual	160	119	103	127.3	29
Fresnel Lens	Astigmatism	252.5	237.3	358.2	282.7	65.8
	Coma	113.3	156.3	84.8	118.1	36.0
	Spherical Aberration	-689.8	-417.6	-1078.3	728.4	332.0
	PV Sphere Residual	460	392	493	448.3	52
	RMS Sphere Residual	75	62	90	75.7	14
Blaze Grating	Average Step Height Error	8.02%	6.96%	5.75%	6.9 %	1.10%
Wedding Cake	Average Step Height Error	0.93%	0.88%	0.83%	0.90%	0.08%

Not shown in the Table was the best power transmission which was 92% of the open aperture measurement. The power transmission was most effected by nozzle temperature and screw rotation speed.

The substrate co-molding experiments were performed to create adhesion between the polymer and the glass capable of withstanding the interfacial stresses due to the mismatch in coefficients in thermal expansion between the glass and the polymer. This mismatch is needed in the system so that the substrate can prevent the thin polymer optic from changing dimensions as thermal conditions change. Thermal stress analyses predicted that the polymer and substrate would be capable of withstanding the stresses induced during the cooling of the polymer after molding, but strength of the bond was still unknown. To test this bond, the lenses were molded and then monitored to determine the amount of time that the adhesion remained before the interfacial stresses became too great and separated the materials. This separation could be observed due to the interference patterns that appeared in the small gap between the polymer and substrate.

As determined by the length of time before delamination, the acrylic lenses were found to have better adhesion with soda lime glass than to fused silica or borosilicate glass. Though the soda lime glass has many more “impurities” than the other glasses, the coefficient of thermal expansion is somewhat higher, thus reducing the stress between the glass and the polymer.

Of the cleaning methods, JTB1-1-1 showed the best results for promoting adhesion. This method had the best results whether silane surface modifiers were used or not. An organofunctional silane was used to promote adhesion as well. Though this surface modifier did help, it did not work as well as expected. It is suggested that this poor performance may be due to possible impurities in the solution chemicals, inaccuracies in the measuring and mixing of the solution, and water absorption of the substrate surface prior to coating.

Most of the co-molded optics for this research delaminated to some extent within 30 minutes. The best result was achieved for a lens that was co-molded and then left in the mold to cool slowly overnight. This optic had good adhesion to the substrate and was able to withstand a load of 7.5psi as produced in a shear test. At that value, the 150µm thick polymer lens fractured.

This research found the injection molding process to be quite capable of producing quality meso and micro optics in common optical polymer. The research also showed the injection molding factors with the greatest effects on replication accuracy as measured by geometric form and light transmission capability. A series of experiments were performed to co-mold optics onto thermally stable substrates. These experiments identified materials that promoted adhesion, but no method was found that created permanent adhesion between the polymer and substrate.

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