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Injection moulded lens array for imaging application

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Abstract
An optical lens used in imaging applications needs typically a sub micrometre form accuracy and a nanometer level surface roughness to perform as designed. There are many variables in an injection moulding process which are effecting the form accuracy of part. The objective of this study is to optimize a plastic part design, tooling and the moulding conditions for imaging quality plano convex lens. In this study a spherical plano convex lens was designed and injection moulded. Mould inserts were manufactured using a single point diamond turning and the moulding was done by using a standard injection moulding machine. The moulded lens surface shape and surface roughness were measured with interferometers. The interferometrical measurements showed a 0.3 microns deviation from the designed spherical shape. The surface roughness of 20 nm was observed. The study shows that in addition to the process parameters product design also plays a vital role in the injection moulding of the lenses.

Plastics optics, imaging, injection moulding

1. Optical Design

The optical design of the plano convex lens was done using the Lens maker's equation [1]. The equation can be greatly simplified because the lens thickness d (3 mm) was very small compared to the lens surface radius. According the lens makers equation for the focal length of 120 mm and COC material n=1,526 (880 nm) a radius of 63,12 mm was calculated. The wavelength was selected according to the final application of the lens.

2. Plastic Part and Mould Design

The design classical way of designing a plastic lens consists of side injection gating, lens and lens framing [2]. Injection moulding of such a design over diamond machined mold inserts is rather straight forward work. However with such a design below micrometer form accuracy of molded lens is difficult to achieve even by using compression moulding, hot runner system and variotherm process.

To avoid warpage, geometrical errors in spherical shape, internal stresses and shrinkage of the injection moulded lens a non-traditional lens design approach was generated. This design consisted of four lenses in rectangular plate with centre gating (Fig. 1.). The final shape of the lens (Diameter 10 mm) can be cut out from the frame by lasering or milling.

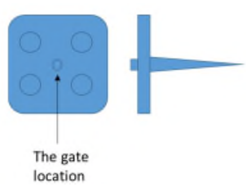

Figure 1. The part design for the four lens array.

3. Lens manufacturing

Diamond turned inserts are typically used for optical quality injection moulded parts. The standard way to program diamond turning machine tool is to use mathematical equations to calculate the machining tool paths. On the other hand part desigers, mould designers and mould makers prefer to use standardized CAD/CAM data formats such as STEP (Standard for the Exchange of Product) for their work. In real life, parts are containing multiple surfaces and it would be preferable to use standardized data format throughout the entire designing and manufacturing chain. A four lens design was made in PTC Creo CAD-program to test how the lens part design in STEP format can be used in optical quality diamond insert manufacturing. The Creo lens array design consists of four individually modelled spherical lens surfaces and rectangular planar surfaces. Small 10 µm edge radius between lenses and planar surface was also designed. Mould design and mould insert designing was also done on Creo system and Moldflow Adviser was used to check for volumetric shrinkage and mould filling.

The mould insert design was translated into a STEP file and imported into Rhinoceros CAD-program. In Rhinoceros 700 000 points were projected on the optical surfaces and the point-file was then translated into Diffsys program for three axis (XZC-direction) spiral lathing tool path programming.

The spiral type toolpath cutting of the multi lens insert, on MS358 naval brass, was done with a Moore 350 FG ultraprecision diamond machine. An inverse time spiral toolpath with 7 µm sidestep, 1 µm point interval and 8 um depth of cut were used. The optical insert was machined with a 1 mm radius diamond tool. Using the cusp height, tool nose radius and sidestep these values would give about 8 nm R_a surface roughness for the inserts. After the diamond turning, the insert was analysed using Keyence VHX-600 microscope camera. Machining errors were located at the junction of each individual lens and the planar surface. It was concluded that the errors originated from the STEP file translation. When the original STEP file design of the part was imported back to Creo it was noted that the modelled lens surfaces, edge radiuses and planar surface were no longer joined together. There were a slight gaps between surfaces. These gap errors had gone through toolpath generation chain. These issues were eradicated by remodelling the surfaces in Creo, surfaces were re-connected with each other as tangentially continuos surfaces. Tangentialy continuos surfaces have a smooth transition between adjoining surfaces. New STEP file was generated and the maching process was repeated without changing any parameters. This time the machining process with correctly joined surfaces gave high quality optical inserts without errors.

Poorly machined surfaces are common error in optical quality moulding and following data translation issues can cause them:

- A surfacing tolerance of the CAD software is set too low, when STEP files are being generated from low accuracy surfaces. There will be gaps and misaligned surfaces in the outputted STEP file
- Old version of standard data translators between systems are being used
- The original optical designing accuracy is lost in part designing, mold designing and manufacturing chain: use of multiple design programs and multiple data translations cause loss of surfacing accuracy
- Sharp edges between surfaces cause problems, adding a very small radius between sharp corners makes transition between surfaces smoother surface. Surfaces should also be modelled as tangentially continuous

The shape of brass lens cavities were measured with Fisba µPhase2 interferometer. WYKO NT9300 white light interferometer was also used to measure the surface topography of machined insert. All the brass cavities were measured with both interferometric systems. The form and surface roughness results are given in Table 1.

Table 1. The shape and the topography of the brass insert

Brass insert	WYKO PSI R_a (nm)	WYKO PSI R_q (nm)	Fisba P-V (µm)	Fisba radius (mm)
Planar surface	8,86	18,10	-	-
Cavity 1	19,13	24,90	0,23	63,24
Cavity 2	19,75	24,80	0,26	63,28
Cavity 3	25,89	35,90	0,23	63,27
Cavity 4	21,37	26,90	0,26	63,29

Moulding experiments were carried out with polymethyl methacrylate (PMMA) and cyclo olefin copolymer (COC). The spherical geometry of the moulded lenses were analysed using Fisba laser interferometer and injection moulding parameters were optimized to get the best spherical shape. PMMA and COC parts were measured and results of the spherical shape were compared. The replication of the spherical shape was better with COC and this material was selected for further study. The most effective moulding process parameter for the shape accuracy was the holding pressure. Holding pressure was varied between 50 – 90 bar pressure and clear improvement was shown due to higher pressure. The effect of holding pressure is significant as can be seen on Fisba µPhase2 measurements of the form accuracy on Table 2.

Table 2. The shape accuracy of the COC lenses as the function of holding pressure.

COC lenses	P-V (µm) at 50 bar	P-V (µm) at 70 bar	P-V (µm) at 80 bar	P-V (µm) at 90 bar
Cavity 1	3,66	0,41	0,42	0,37
Cavity 2	3,82	0,51	0,38	0,37
Cavity 3	3,72	0,52	0,44	0,44
Cavity 4	0,89	0,81	0,51	0,35

At the 50 bar holding pressure the shape accuracy is round 4 microns whereas with 90 bar holding pressure the accuracy drops to less than 0,5 microns. The uniformity between brass cavities and moulded lenses is extremely high as can be seen (Fig.2.).

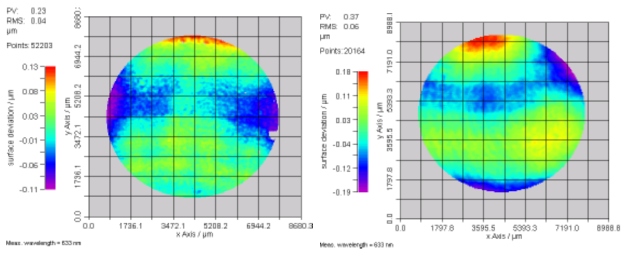

Figure 2. Fisba form measurements a) cavity number one form and b) COC lens at 90 bar holding pressure from cavity number one

Surface topography of four lens array at 90 bar holding pressure was measured with WYKO NT9300 white light interferometer. These results are given in Table 3.

Table 3. The topography of the lens array.

Lenses 90 bar holding	WYKO PSI R_a (nm)	WYKO PSI R_q (nm)	Fisba µPhase P-V (µm)	Fisba radius (mm)
Planar surface	14,43	19,05	-	-
Cavity 1	20,57	31,03	0,37	63,15
Cavity 2	19,95	25,85	0,37	63,23
Cavity 3	20,90	28,26	0,44	63,12
Cavity 4	19,62	25,06	0,50	63,24

5. Summary

Experimental results showed that the injection moulding process is capable for precision optics manufacturing. The study shows that in addition to the process parameters the product design also plays a vital role in the injection moulding of the lenses. The measurements confirmed the initial conclusion that the plastic part design has important role in molding od plastic optics. The STEP based geometries can be used for optical quality machining but issues concerning modelling accuracy and techniques need to be properly addressed.

References

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