High Precision Injection Moulding of Freeform Optics with 3D Error Compensation Strategy

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Abstract

Injection moulding offers a cost efficient method for manufacturing high precision plastic optics in high volumes. In connection with the demand for freeform optics in imaging optical systems like head mounted devices or head up displays [1], unsymmetrical shrinkage compensation strategies have to be developed to realize freeform optical surfaces with high precision for high volume applications.

This paper describes an efficient method for significantly increasing the form accuracy of injection moulded freeform optics. In this regard, a typical plastic freeform optics has been designed, moulded, and commonly optimized by main moulding process parameters. The process-related shrinkage of the freeform optics generated a non-rotationally symmetric surface error. To compensate for such kind of non-uniform shrinkage, a freeform error surface had to be superimposed to the freeform design surface on the mould. Regarding the measurement analysis, two strategies are discussed. The first method is a best-fit procedure and in the second case, well defined reference structures are used. In conclusion, the systematic form deviation can successfully be pushed from the typical range of illumination optics into the level of some imaging applications at moulded plastic optics.

1 Demonstrator design, mould- and process optimization

For analysing the process chain, a typical freeform optics was defined and specifically modified for the processing with injection moulding. The demonstrator design, the mould design as well as the cavity manufacturing process are shown in figure 1. The freeform surface is described by a Zernike polynomial function and has

a clear aperture of 44 mm with a part diameter of 70 mm. The reference structures are defined by three spheres (3 x 120°) with a convex radius of 10 mm on a reference circle of 58 mm.

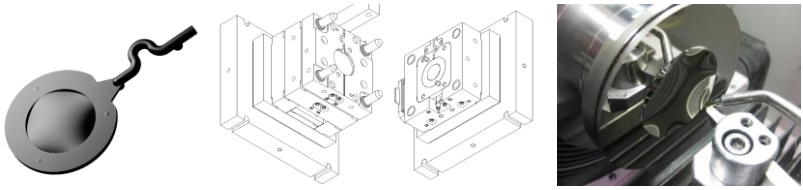


Figure 1: Lens design, mould design, and mould machining with Slow Tool Servo

In order to achieve sub-µm accuracies of smaller than 0.5 µm p-v at the mould, a procedure already shown in [2] was used. Based on the high precision mould, optimizations at the moulding process were done. So at least the main influence parameters (melt- and mould temperatures, dwell pressure, dwell pressure- and cooling times) [3] were systematically modified separate with respect to the form deviation. Afterwards, a 3^3 experimental design was realised. Optimal process parameters were defined and checked with FEM simulation methods. Main results of a 3^3 experimental design are shown in figure 2. An optimal process was found at 1000 bar dwell pressure and 240°C melt temperature at a mould temperature of 90°C. The process scatter seems to be a random, but for the defined process optimal as well.

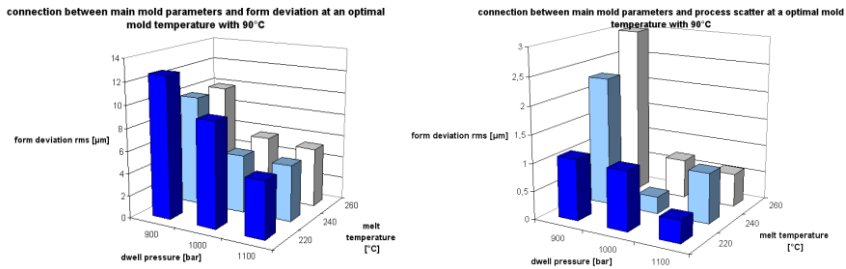
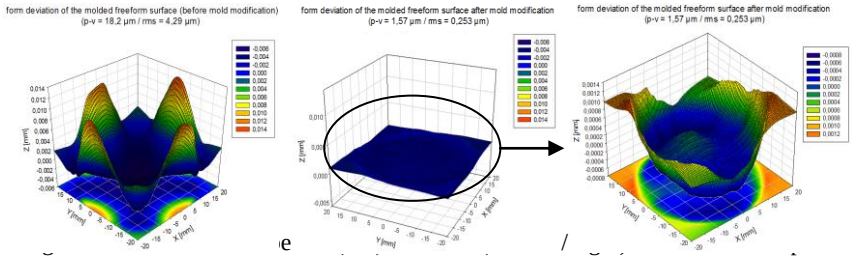


Figure 2: Main influence moulding parameters on form deviation and process scatter

2 3D error compensation based on the best-fit strategy

Moulding the freeform optics with optimal process parameters, a median form deviation of the moulded parts was calculated, taking into account measurements of the 2½D profilometer of Panasonic UA3P. The measured points cloud was tilted and shifted in all 6 degrees of freedom by using the least square method. In order to

compensate the 3D shrinkage of the moulded freeform surface, the form deviations were averaged and superimposed to the mould design surface at right locations. Further parts were moulded with the same process parameters. In conclusion, the form deviation was reduced from 18.2 µm p-v / 4.29 µm rms to 1.57 µm p-v /0.25 µm rms.



3 3D error compensation based on reference structures

In order to determine the form- and position errors [4], the moulded freeform surface and the three reference spheres were measured in one setup at the 2½D profilometer. Subsequently, a new coordinate system based on the 3 reference points was build to fix all 6 degrees of freedom. The measured points cloud was compared with the mathematical description. The initial error based on this process is shown in figure 4, left. Results seem to be similar to the measured data of the best-fit deviation in figure 3, left. The reason is that the references are realised high precisely in one setup with the freeform surface itself. Furthermore, the shrinkage of the moulded part is very symmetric, so that the reference points are able to shrink homogeneously, directed to the centre. After the first iteration loop, a deviation map with about 6.0 µm p-v / 1.1 µm rms was measured. Compared to other investigations of this batch, the error map did not appear systematically and thus, further iterations based on this method were not useful. The fact is caused by existing measurement uncertainties and process scatters at more elements on the part.

By using an additional best-fit procedure on the error map, final tilt errors of 0,0056° around the X and -0,0029° around the Y axis as existing main position error in this case was detected. In consideration of this, a final form deviation of 1.65 µm p-v / 0.28 µm rms can be calculated.

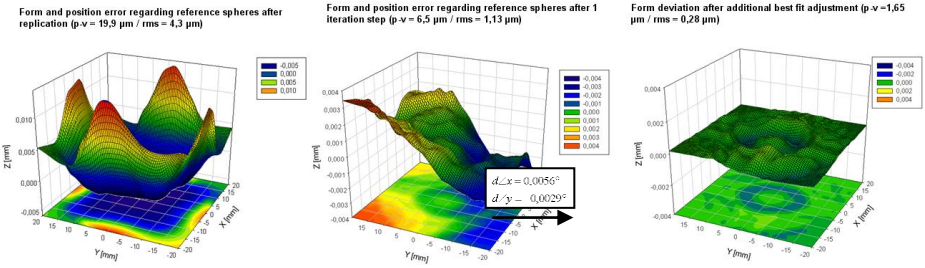


Figure 4: Form- and position error before (left) and after (middle) the first iteration loop, and resulting form deviation after an additional best fit procedure (right)

4 Summary

Due to several process parameters, moulding freeform optics lead to an influence of the form deviation. Finding an optimal combination, usually high systematically errors can be measured by using different analysis strategies. The asymmetric systematic deviation map can be superimposed to the design surface at the mould. Depending on the measurement analysis method, accuracies of less than 2 µm p-v and of about 6 µm p-v were reached successfully on a demonstrator surface by using the best fit strategy and by using the reference marks, respectively. For this, optimal process parameters provided only about 20 µm.

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