Manufacturing of Freeforms with well defined Reference Structures

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INTRODUCTION

Modern freeform designs are pushing the performance of optical systems used for beam shaping, beam homogenization as well as for imaging optics [1, 2]. However, without a tight relation between the optical and the mechanical coordinate system, even the most sophisticated freeform can not tap its full potential within the optical system. Therefore the manufacturing of references in close tolerances to the optical freeform surface is a big challenge. Diamond machining is an excellent technology to meet this requirement.

The present paper summarizes realized machine setups, freeform manufacturing processes as well as the cutting results for diamond machining of optical surfaces and reference structures. The results and investigations are based on practical examples.

WHY DO FREEFORMS NEED REFERENCE STRUCTURES

Classical rotationally symmetrical optics need tolerances for figure deviation, surface roughness, cleanliness etc. and for the position of the optical surface in respect to their mechanical boundaries. Well developed deterministic manufacturing techniques (SPTD, grinding, polishing) provide excellent optical surfaces. Nevertheless, without well defined mechanical references, high performance optics can not provide their full potential. In fact rotational symmetrical optics needs references for centering, tilt and vertex height. Over the years specific technologies were developed to push the accuracy for centering and vertex height in the micron and sub-micron range [3]. If the optical element is made of a diamond turnable material, references and the optical surface can be directly turned.

This issue is much more complicated in case of freeform optics because the references must represent six degrees of freedom. The challenges of freeform manufacturing like:

- Freeform measurement
- Refeeding the measurement data into correction loops
- Controlled assembly and adjustment strategies
- Repeatable positioning / clamping during manufacturing and assembly

are feasible only with well defined fiducials.

MANUFACTURING OF FREEFORMS AND REFERENCES BY DIAMOND MACHINING

Diamond machinable materials have the advantage, that all precise geometries, including the optical surface, references and respectively the mechanical boundary can be manufactured on one machine. However, in most cases several manufacturing techniques like servo turning, milling or shaping are necessary to produce the references and the freeform surfaces. One promising approach is to realize multiple cutting techniques in the same machine setup.

FIGURE 1. Design example of an optical freeform element with reference structures.
Combining Shaping and Turning

Shaping – known as a typical ultraprecise process for micro structuring – offers an excellent alternative for freeform manufacturing. Especially steep surfaces or freeforms without rotational symmetry are preferred shapes for 3D shaping. Using the machine setup, illustrated in figure 2, both shaping and diamond turning are possible in one setup and with one and the same tool. The machining technique is based on a four axis ultraprecision machine. During the shaping process the Y and Z axis are moving synchronously along the calculated tool path. The X - axis works in raster respectively positioning mode. The Y axis is equipped with a diamond tool. Measurement probes can also be mounted on to the Y – axis to reference the workpiece according to the machine coordinate system. The rotational C-axis allows the positioning of the workpiece with high precision in Rz or can act as a turning spindle.

The setup was used for optical elements with one freeform side and one rotationally symmetrical side (figure 3). Due to the use of one tool, both optical surfaces have a tight positioning tolerance. A rotational symmetrical reference and mounting structure was also turned. Beside this application it is also possible to manufacture a freeform by servo turning and adding references by shaping.

This approach is typical for polymer optic prototypes. In this case the prototype consists of one rotationally symmetrical element and one freeform element. The optical axes of both surfaces are located in the spindle centre. Therefore the alignment and the referencing of the part are easy, because the tool can be aligned in a similar way to SPDT. The Tool position (0, 0, 0) represents the origin of the optical coordinate system. The optical surface description can be used directly for creating the machining data.}

Combining C-Axis Milling and Turning

Slow-Tool machining offers a good way to manufacture freeforms that can be separated into a rotational symmetrical and a freeform component with moderate slope angles. An integrated C-axis milling process is a potential solution for the manufacturing of reference structures in a close relation to the optical surface.

The arrangement of references must be capable of determining the position of the optical surface in all degrees of freedom. Therefore three
references on a common pitch circle or more elements on different diameters must be machined in a fixed position on the substrate to represent the axis of rotation. These alignment marks embody the coordinate system of the lathe and the manufacturing process of the part. It can be used to transfer the information about the position of an optical surface into the metrology. This allows avoiding the usual necessary alignment fit of the measurement data respectively the target surface in 6 degrees of freedom to calculate the form error of the surface.

The reference marks must be capable of being detected within sub-μm range during the measurement. Spherical references with steep slopes are suitable for the position detection with tactile measurement devices like 2½ D profilometers. But the slopes are limited using the Slow-tool machining. Therefore an additional milling spindle can be mounted next to the turning tool in the UP-lathe.

**Figure 5. Basic Setup for combined C-Axis-Milling and Turning: Spindle/C-Axis with freeform work piece, Turning tool, additional milling spindle.**

Essential for such a Slow-Tool servo setup is the proper alignment of the milling tool to the C-axis and the turning diamond. The tool must be aligned within sub-μm range to the axis of the turning spindle. A careful tool setting is achieved by milling specialized test geometries to analyze the tool decentration in each direction independently. After a precise tool setting, the tool can be aligned within a micron to the axis of rotation of the C-axis.

But also the programming of the tool path is challenging. Due to the off-axis position of the reference elements on the substrate, its geometry has to be treaded as a freeform [4]. The machine kinematics of the UP-lathe consists of two linear axes (X, Z) and one rotational C-axis.

A proprietary software solution had to be programmed for the generation of the tool path. The trajectory of the tool center point follows an Archimedean spiral in an off-axis position to cut the reference spheres. The path is generated by adding the normal vector of the surface with the length of the tool radius to the position vector of the node from the origin of the coordinate system.

**FIGURE 6. Toolpath trajectory for the c-axis milling derived from the contact point of the tool with the surface.**

A following shift to the desired position on the substrate and a coordinate transformation leads to the point cloud that can be interpreted by the machine using a smoothing spline interpolation. The resulting machine motion is a synchronous oscillation of the C-axis and the X-axis, while the material is removed by the mono-crystalline diamond tool.

**FIGURE 6. Form error of an off-axis mirror measured with a profilometer and aligned according to milled reference marks. Shape irregularities 380 nm p.-v. inside the quality area.**
The 2½D profilometer Panasonic-UA3P offers the ability to measure the reference marks and the optical surface in a high accuracy regarding form and position. The reference marks, which embody the coordinate system of the UP-lathe, are used to find the quality area of the optical surface and the tilt about the X, Y, and Z axes. A subsequent alignment step according to the measured angles results in the true form error of the surface. This approach is especially useful for geometries which do not contain a vertex, like off axis mirrors and freeform mirrors.

CONCLUSION

The combination of different diamond machining techniques in one machine setup opens up the flexible manufacturing of freeform optics with well defined reference structures. One key issue of freeform manufacturing – getting confident measurement data and refeeding it in the correction loop – can be solved. Therefore mechanical references or optical fiducials are machined in sub-micron relation to the optical surface. Especially in the field of high performance mirrors for telescopes the excellent positioning of the optical surfaces are of particular importance. The proposed techniques enable for a deterministic and precise mirror mounting and system assembly process.

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REFERENCES


