Ball-end Milling of Free-form Surfaces for Optical Mold Inserts

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Abstract
One of the objectives of the Transregional Collaborative Research Center SFB/TR4 of the Universities of Aachen and Bremen, Germany, and Stillwater, Oklahoma is the development of diamond machining processes for metal molds integrated in the process chain for economic mass production of complex optical elements.
In this paper we will discuss the application of diamond ball-end milling for machining of free-form surfaces with small radii of curvature, the generation of NC-programs, requirements on tool alignment and a new high-resolution method for measuring surface slopes, local radii of curvature and figure error of free-form surfaces based on fringe reflection. Surface definition by NURBS is used throughout the process chain from the design stage to mold manufacture, injection molding and testing. The aim of the work presented in this paper is to minimize the number of iteration loops needed for achieving the required surface quality.

Keywords: Diamond ball-end milling, complex surfaces, NURBS, fringe reflection

Introduction
Typical process chains for economic mass production of complex optical components like aspheres, free-form surfaces and structured surfaces include optical design, mold fabrication and replication. If the replication process (e.g. injection molding of plastic lenses or compression molding of glass lenses) does not yield perfect, but repeatable results with constant figure errors, these can be compensated by adapted molding (1). Such surface deviations, caused by inhomogeneous shrinkage and / or other subtle and difficult to control effects, often introduce local radius of curvature errors, whose compensation affords an adequate and flexible machining technique for modifying the mold surface. The most universal technique, also capable of coping with small positive and negative radii of curvature, is diamond ball-end milling (2).

Ball-end milling
The smallest radius of curvature that can be machined by ball-end milling is the radius of the diamond tool. However, machining time is proportional to the inverse of the tool radius, if surface roughness is to be maintained.
Ball-end milling is usually performed with half-arc single crystal diamond tools mounted on a steel shank (Fig. 1a). The achievable figure accuracy of the milled cavities strongly depends on tool alignment. The vertex of the cutting edge must be aligned to coincide with the spindle axis, which was realized with a newly developed adjustable ultra-precision tool holder. Centering of the tool was performed with the help of an optical microscope. Tilt alignment can be done by milling of test cavities and evaluating the created contour with a white-light interferometer (WLI). The setup for tool alignment with an optical microscope is shown in Fig. 1b, while a view on the rake face of a half-arc diamond tool is shown in Fig. 1c. The vertex of the tool could be aligned within 1 µm with respect to the rotational axis and the tilt angles χ and ψ could be set < 0.01°.

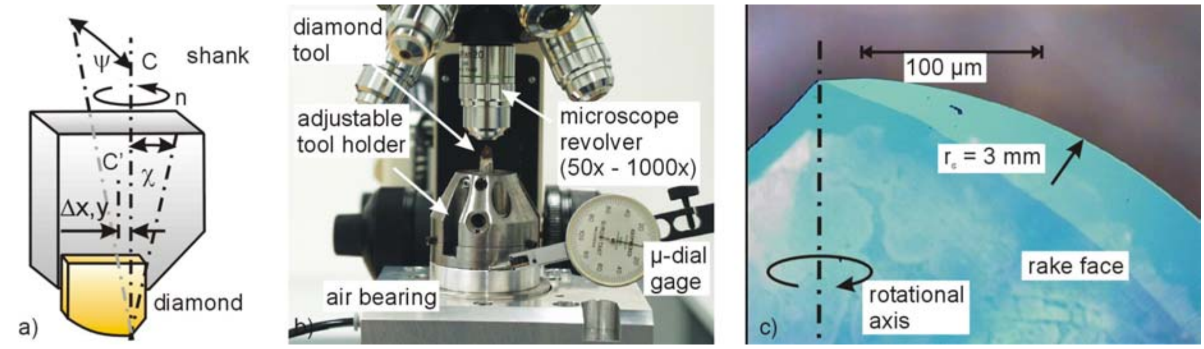

Fig. 1: Schematic view of a half-arc ball-end milling tool and degrees of freedom for alignment (a), setup for alignment with an optical microscope (b), view on the rake face of a half-arc diamond ball-end milling tool (c).

For first milling experiments specimens with ∅ 80 mm were used made of OFHC-Cu, AlMg3 and electroless nickel (NiP). As can be seen in fig. 2, the specimens were designed as inserts for subsequent injection molding of test plates. 6 x 6 matrices were machined by ball-end milling with different diamond tools with nose radius varying between r_ε = 2.5 mm and 5 mm, and with different feed velocities and rotational speeds varying between v_f = 30 mm/min and 200 mm/min and n = 1,000 rpm to 6,000 rpm, resp. The angle between the normal vector of the surface and the axis of rotation was varied between γ_{tilt} = 0° and 40°. The achieved surface roughness, measured with a WLI (cf. Fig. 2b) over an area of 500 µm x 500 µm, was between Ra = 5 nm and 25 nm for NiP and Ra = 15 nm and 40 nm for OFHC-Cu and AlMg3.

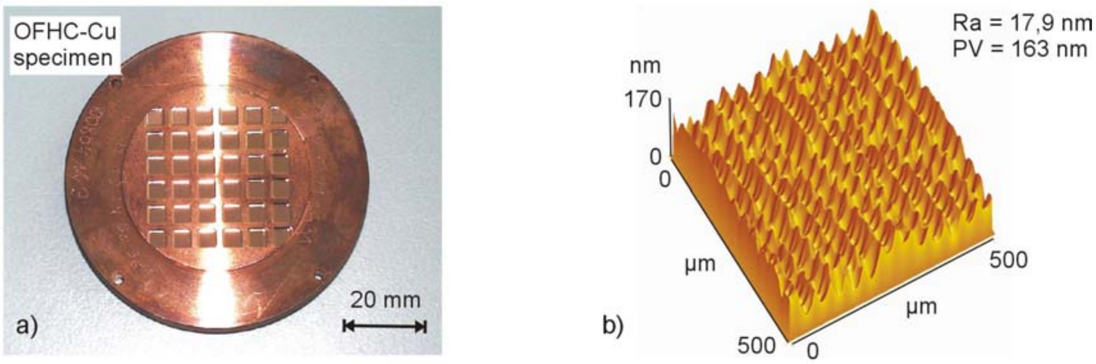

Fig. 2: a) 6 x 6 matrix machined by ball-end milling in OFHC-Cu with different machining parameters.
b) WLI-image of typical ball-end milled OFHC-Cu surface.

Test machining of a free-form surface

Within this work, the NURBS (non-uniform rational B-splines) concept was used as an universal tool for progamming the tool path for ball-end milling operations of free-form surfaces as well as for figure testing and retrofitting of measurement results (cf. Fig. 3) (3).

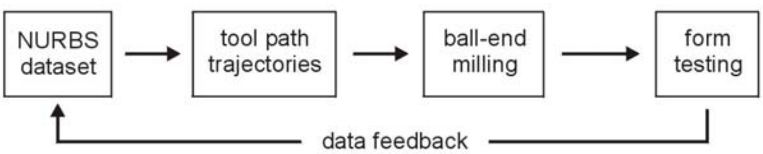

Fig. 3: Basic approach for retrofitting of surface data.

As an example, a free-form mirror surface described by NURBS was machined by ball-end milling which was tailored for projecting the light from a point source onto a screen yielding the logo of the SFB/TR4 (Fig. 4). The mirror surface and the generated tool path for spiral ball-end milling (including tool radius compensation) is shown in Fig. 5. The maximum departure from a plano surface was 1.4 mm. The total cutting distance was 140 m.

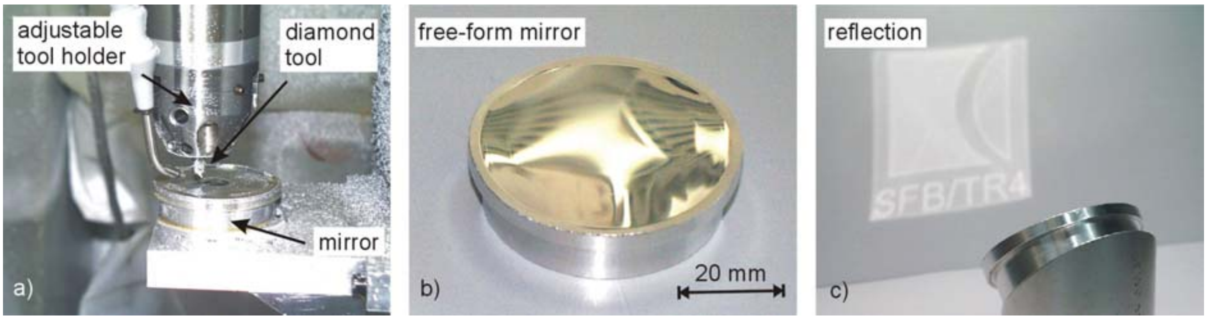

Fig. 4: Experimental setup for ball-end milling on a Precitech Freeform 3000 (a), machined free-form mirror (b) and projection of the SFB/TR4 logo (c).

Ball-end milling was performed on a Precitech Freeform 3000 multi-axis ultra-precision machine using a carbide tool for pre-machining and a half-arc diamond tool with a nose radius of 3 mm for finishing. The increment of the spiral trajectory was 15 µm. Milling was performed at a rotational speed of n = 4,500 rpm with a feed v_f = 125 mm/min. The surface roughness of the milled aluminum mirror was < 20 nm Ra.

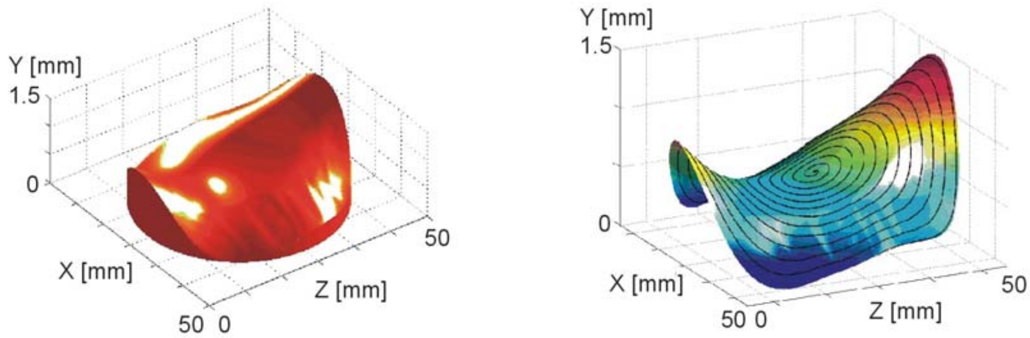

Fig. 5: Free-form mirror surface (CAD simulation) and tool path with spiral infeed for ball-end milling.

Surface inspection by fringe reflection

Easy and fast assessment of the form accuracy of the machined free-form mirror surfaces was achieved by a newly developed fringe reflection method, whereby a TFT monitor projects black and white fringes onto the specimen. The reflected fringe pattern is viewed by a video camera and analysed by a propriatory software routine. Thus, the reflection angles can be determined for every camera pixel and the local gradients can be calculated with high lateral resolution. The surface data are obtained by integration. The vertical resolution is much better than in fringe projection and is in the range of 1 nm. A setup for fringe reflection measurement is shown in Fig. 6a. The reflected fringes and measured slopes in the x- and y-direction are shown in Fig. 6b and 6c, resp.

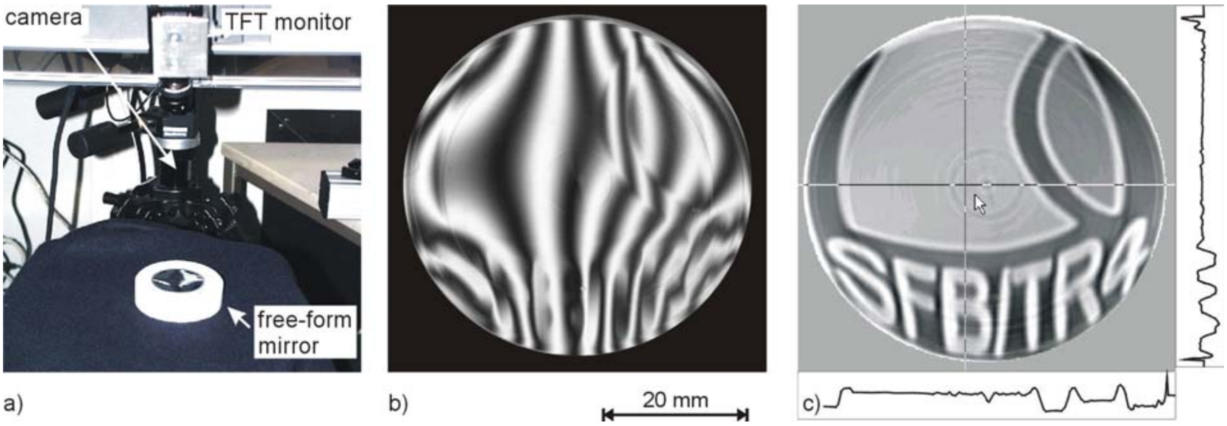

Fig. 6: Measuring setup for fringe reflection (a), reflected fringes on free-form mirror (b) and calculated surface slopes (c).

Summary
In this paper we have presented first results of diamond ball-end milling of free-form surfaces based on NURBS which will form an integral part of the production chain for producing high quality complex optical surfaces developed within the Transregional Cooperative Research Center SFB/TR4. Moreover, we have introduced a new powerful method for the assessment of surface slopes on free-form surfaces by fringe reflection. Both methods will be used in future work providing a basis for economic mass production of aspheres and free-form surfaces by mold fabrication and replication.

Acknowledgement
The research work presented in this paper is part of the SFB/TR4 “Process Chains for the Replication of Complex Optical Elements“, funded by the DFG German Science Foundation. The free-form mirror was designed by OEC AG, Munich, Germany. The figure testing of the free-form surface producing the SFB/TR4 logo by fringe reflection was performed in cooperation with BIAS, University of Bremen.

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