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Diamond Micro Chiseling of retroreflective arrays on curved surfaces

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Abstract

Hexagonal retroreflectors are highly efficient optical microstructures for safety or measurement applications. Arranging these retroreflectors on a curved surface enables new possibilities of optical features. Diamond Micro Chiseling (DMC) was specifically developed for the generation of hexagonal retroreflector-arrays with structure sizes between 50 and 500 µm on plane surfaces.

This publication will focus on the requirements that need to be fulfilled for applying Diamond Micro Chiseling on curved surfaces. This includes the necessary calculations for aligning the structures to the curved surfaces as well as tool-setting procedures that include the rotation of a rotary table (B-axis). Knowing the geometry of a curved surface and the cavities as well as the cavities' position on the surface, the structure alignment can be calculated for every facet of the retroreflector array. Using a sphere as base geometry, each structure has a different orientation, quickly resulting in several hundred different orientations of the tool and thereby the rotary table. Due to the offset between the tool centre point (TCP) and the centre point of the rotary table, the tool is rotating on a circular path around the expected centre point of the rotary table. Consequently, the B-axis has to be integrated in the tool alignment process. As not all angles can be aligned individually, a circle interpolation is used to minimize the necessary tool alignment steps. The feasibility of this method will be demonstrated by a qualitative analysis of structural deviations, resulting from alignment errors.

Diamond Micro Chiseling, hexagonal retroreflectors, curved surface

1. Introduction

Technical surfaces are enhanced with additional functionalities by microstructures [1] e.g. to advance safety applications with optical microstructures, like retroreflective surfaces [2]. However, the chosen machining process for the desired optical microstructures is crucial to fulfil optical requirements [3]. For the generation of hexagonal retro-reflector-arrays with structure sizes between 50 and 500 µm on plane surfaces, the Diamond Micro Chiseling (DMC) process was purposefully developed [4]. Due to the process kinematics, three linear and one rotary axis are required for the generation of cavities on plane surfaces. Arranging these retroreflectors on curved surfaces enables new possibilities of optical features, simultaneously resulting in further requirements which have to be fulfilled. The workpiece geometry, the position and orientation of each cavity on the surface and the tool centre point (TCP) have to be considered.

Using a sphere as base geometry, the workpiece geometry can easily be defined in Cartesian coordinates. However, arranging the structures on curved surfaces requires more calculations. Each cavity of a retroreflector-array on a curved surface has to be aligned to the surface individually. This individual alignment process and the curved surface lead to an angular variety between every facet of each cavity, quickly resulting in several hundred different orientations. Due to this variety and the definition of cube corner retroreflectors, the tool has to be aligned individually for every facet. For realising this tool alignment while machining, a rotary table has to be included into the machining process. Due to the unavoidable offset between the tool centre point (TCP) and the centre point of the rotary table, the tool is rotating on a circular path around the expected centre point of the rotary table (cf. Figure 1).

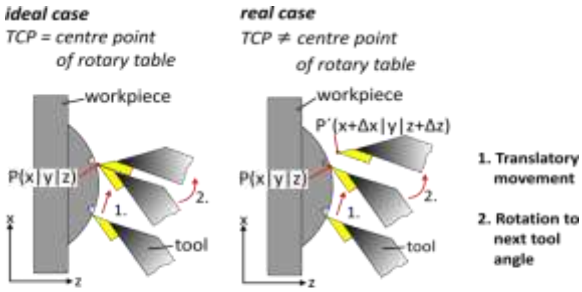

Figure 1. Tool rotation in an ideal and in a real process case.

Consequently, the B-axis has to be integrated in the tool alignment process. As not all angles can be aligned individually, a circle interpolation is used to minimize the necessary tool alignment steps. Therefore the already presented tool alignment procedure for DMC [5] has to be expanded for an additional rotary axis. Depending on the measurement accuracy in the tool alignment process, the deviations in the interpolated TCPs result in structural deviations.

In this investigation, the feasibility of an interpolated angular tool alignment for Diamond Micro Chiseling on curved surfaces will be discussed by analysing machined retroreflector-arrays qualitatively.

2. Methodology

The expanded tool alignment procedure to facilitate DMC on curved surfaces was divided into multiple steps. After defining the workpiece in Cartesian coordinates and calculating the position and orientation of every cavity on the curved surface, the required tool rotation range was calculated. This range was divided into equal angular increments to reduce the complexity of the alignment procedure. After measuring the deviations in x- and y-direction from the alignment structures at each increment using a SEM (Hitachi TM3030Plus), a circle interpolation was used to calculate the tool rotation centre coordinates and the radius of the tool rotation circle. Thereby the TCP can be interpolated for every tool angle for the retro-reflector-array.

This data was used to carry out DMC experiments using a five axes ultra-precision machine tool (Nanotech 350 Freeform Generator [x-axis straightness: 0.3 µm over 350 mm; y-axis straightness: 0.5 µm over 150 mm; rotary axes positioning accuracy: ± 1.0 arc seconds] [6]) to generate hexagonal retroreflector-arrays. A spherical nickel silver workpiece was used to machine multiple retroreflector-arrays on an area of 10x10 mm² (c.f. Figure 2) with varying deviations in the circle interpolation, resulting from artificially induced measurement errors in the tool alignment process, shown in Table 1.

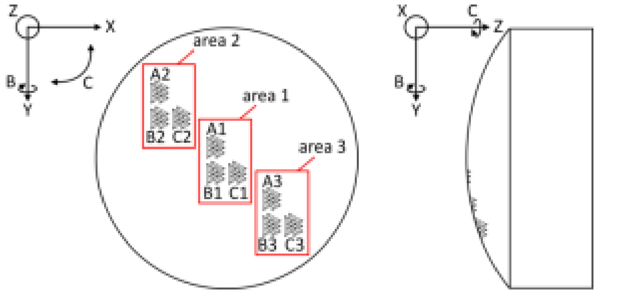

Figure 2. Retroreflector-array positions on spherical nickel silver workpiece.

As baseline the presumed best measurements in the alignment process were used in group A. Due to the DMC process kinematic, only x-axis alignment errors result in a deviation of the circle interpolation (group B). The y-axis alignment errors are a static value, not influencing the circle interpolation, however, influencing the cavity geometry, therefore artificial errors in y were introduced to group C.

Table 1. Artificially induced errors for DMC machined retroreflector arrays of group A, B and C.

group / tool angle	A		B		C	
	x-error in µm	y-error in µm	x-error in µm	y-error in µm	x-error in µm	y-error in µm
46.0°	± 0	± 0	+ 0.5	± 0	+ 0.5	+ 0.5
48.5°	± 0	± 0	- 0.5	± 0	- 0.5	+ 0.5
51.0°	± 0	± 0	+ 0.5	± 0	+ 0.5	+ 0.5
...	...	...	...	...	...	...
67.0°	± 0	± 0	+ 0.5	± 0	+ 0.5	+ 0.5

Each group was machined in different areas of the curved surface. This magnifies the influence of the calculated circle interpolation, as the tool has to rotate over a wider range of approx. 16.5° near the edge of the sphere, while near the spherical centre, the tool rotates over approx. 3°.

3. Results and Discussion

The optical performance of retroreflective elements is affected by structural deviations. For DMC machined retroreflector-arrays, deviations in the crossing point of three cavities, i.e. six facets, will be used as an indicator for the alignment accuracy. Figure 3 shows the crossing points from selected retroreflector-arrays on the curved surface.

The results in Figure 3 indicate that even small deviations below 1 µm in the tool alignment process affect the generation of the retroreflector-array considerably. Consequently, the optical performance is affected by the arising artefacts. The cavities' crossing points near the spherical centre (A1, B1 and C1) show no significant difference.

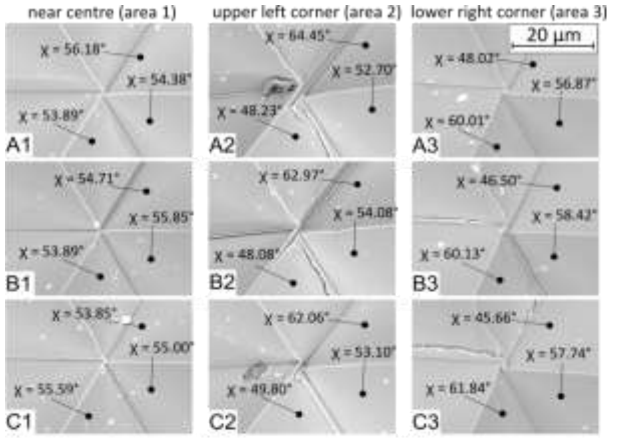

Figure 3. SEM images of DMC machined hexagonal retroreflector arrays with varying tool alignment angles X of approx. X = 53-56° (A1, B1, C1), X = 48-64.5° (A2, B2, C2) and X = 45-60° (A3, B3, C3) for different artificially induced axes alignment errors.

However, A2, B2 and C2 display obvious deviations. With a measurement error of ± 0.5 µm in the x-axis alignment, the structural deviations increase apparently from A2 to B2. The decline of artefacts from A2 and B2 to C2 is of particular importance, showing the baseline alignment (A1-A3) was not ideal. In the third area (A3, B3 and C3) the structural deviations in the crossing points increase with rising alignment errors. Again, the structural deviations in group C with extra y-axis alignment error are apparently smaller than without.

4. Conclusion and Outlook

Diamond Micro Chiseling experiments with artificially induced alignment errors of the machine axes were carried out for machining hexagonal retroreflector arrays on curved surfaces. In order to analyse the resulting deviations in the machined retroreflective structures, a SEM was used.

The results indicate that the expanded tool alignment procedure is applicable to machine hexagonal retroreflector arrays on curved surfaces using a circle interpolation, despite minor structural deviations. Although the measurements of the tool alignment structures were carried out by means of a SEM, the assumed optimal baseline alignment indicates minor structural deviations in larger tool rotation ranges. The visible rise of structural deviations on a curved surface, resulting from tool alignment errors below 1 µm, indicates that the alignment procedure still requires further optimisation.

Consequently, additional research will focus on analysing new alignment strategies with the use of a SEM to further decrease the alignment errors and to exclude any interactions with the circle interpolation.

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