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Enhanced ultra-precision machining of discontinuous microstructures on monolithic surfaces

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Abstract
Discontinuous microstructures are increasingly being used in optical applications to provide technical surfaces with additional functionalities, for example in retroreflective arrays. Due to their essential high shape accuracy, surface quality and dimensional precision, these structures are typically generated in monolithic surfaces by diamond machining.
While rotationally symmetrical structures can easily be created in a turning process, grooved structures have to be created by milling. However, conventional machining processes are not suitable for the production of discontinuous microstructures, hence Diamond Micro Chiselling (DMC) was developed as a sophisticated discontinuous diamond machining process. This process demands a high level of machine tool performance and process stability. Moreover, the machinable pattern size is limited by the current kinematics. Thus, large-area microstructure arrays need to be manufactured in several small segments, which subsequently have to be precisely assembled. This process is tedious and cost-intensive, as well as not capable of achieving the identical level of quality as a single monolithic microstructure array.
To overcome these process limitations, the kinematics and process control of DMC were modified in order to enable the production of microstructures in the entire workspace of the machine tool. This would enable the machining of large scale monolithic surfaces and make the assembly of several small segments obsolete. For this purpose, a multi-axis positioning system consisting of two goniometers and three piezoelectric linear actuators was developed and integrated into a 5-axis ultra-precision machine tool. In addition, the CAD/CAM software developed in-house was extended to enable the production of large-area retroreflector arrays in monolithic mould inserts. With these changes, the machinable area of the DMC process has been increased by more than 500%.

ultra-precision machining, discontinuous microstructures, monolithic surface

1. Introduction

The continuous functionalisation of technical surfaces in optical applications by discontinuous microstructures [1, 2] is rapidly increasing the complexity of design and machining. In optical applications, discontinuous microstructures are used, for example, in retroreflective arrays, micro-Fresnel lens arrays, directional micro grating arrays, as well as in the electronics industry and for microfluidics devices [3, 4, 5]. However, direct manufacturing of discontinuous microstructures is not possible with conventional machining processes (e.g. turning or milling) because of limitations of the kinematics or in the degrees of freedom of the machine tool [6]. For this reason, Diamond Micro Chiseling (DMC) has been previously implemented to manufacture such structures on flat [3] and curved surfaces [7].

DMC in turn sets high demands on the machine tool and process stability for the machining of microstructure arrays, especially when producing structures on large-scale area. Therefore, the microstructure arrays are often manufactured in individual segments and then assembled into a coherent array. However, this assembly process is not only tedious and time-consuming, but also requires the highest precision to achieve a tolerance of 10 µm or better. Nevertheless, even with the best possible assembly, undesirable seams are visible in the final product, reducing product quality. Another reason for manufacturing only small retroreflector arrays with a total area ≤ 100 mm² is the limited working space of the ultra-precision machine tool when using the DMC process kinematics.

By swapping workpiece and tool position, several restrictions of the DMC kinematics, like the required re-positioning after a rotation of the workpiece, can be conquered and the structurable workspace is significantly increased. However, an additional tool positioning system is mandatory for this purpose to set and maintain the required tool orientation. Such a system was developed based on two rotary and three linear axes which are mounted on the main axis of the machine tool. The new kinematic allows the diamond tool to be rotated around its Tool Centre Point (TCP) and enables repositioning in the complete positioning range of the ultra-precision machine tool. Due to the integration of the five additional axes into the ultra-precision machine tool, the manufacturing quality has to be investigated in detail subsequently, as there will be a change in the machine stiffness. Due to the modified process kinematics, a review of the already developed set-up processes will be carried out and, if necessary, adapted and tested accordingly.

2. Tool positioning system

The change of the process kinematics demands an exchange of the workpiece and tool position. Therefore, the workpiece is attached onto the Z-axis of the ultra-precision machine, while the tool is attached to the main spindle at a defined angle, which must be varied according to the structure angle of the facet surface. For this purpose, the positioning system consists of two goniometers (WT100 and WT85) and three piezo linear actuators (Q-545.140) from Physik Instrumente (PI) GmbH & Co. KG. The goniometers are used to adjust the structure angle, while the linear actuators are needed to position the TCP in the pivot point of the goniometers. Without this translational adjustment capability, the machine axes would have to perform a large repositioning in multiple machine axes after each rotation of the tool on the main spindle.

These piezo linear actuators allow the TCP to be adjusted in the Cartesian spatial coordinates X, Y and Z with a positioning accuracy of < 1 µm. The goniometers are equipped with an angle measurement system and stepper motors with a computational resolution of 2.11 µrad. As illustrated in Figure 1, the tool positioning system was integrated into a Nanotech 350FG [8] ultra-precision machine tool (Moore Nanotechnology Systems, LLC) for further testing.

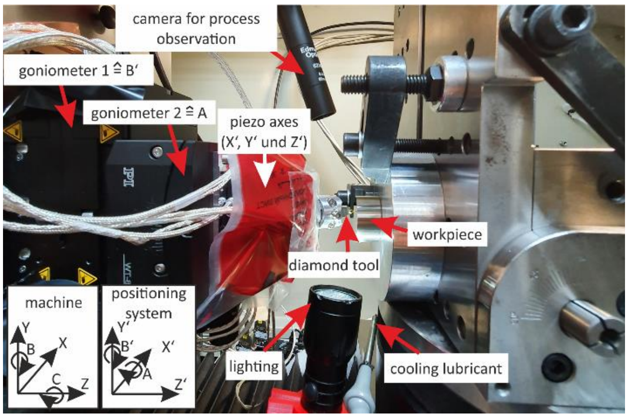

Figure 1. Tool positioning system on main spindle of the ultraprecision machine tool Nanotech 350FG.

3. Tool alignment

3.1. Clearance angle

In order to avoid immediate damage to the tool during the first cutting operation the clearance angle of the tool has to be set first. Since the tool design specifies a clearance angle of approx. 2°, which is guaranteed by the tool manufacturer with a deviation of ≤ 0.1°, an adjustment to ≤ 0.1° is sufficient and can be set up via the C-axis of the ultra-precision machine tool.

Since measuring the diamond edge itself is a technological challenge, the tool shank was chosen as a reference surface. In the tool manufacturing process, the tool shank is ground and the soldered diamond is subsequently processed. Therefore, it was assumed that the tool shank as reference surface has sufficient flatness to conclude the present clearance angle. To measure the tilt of the tool shank, a capacitive displacement sensor was used, which has a measuring accuracy in the nm-range.

Figure 2a shows the measurement setup in the ultra-precision machine and Figure 2b shows the tilt measurement using the capacitive displacement sensor along the tool shank.

During the measurement, the Y-axis of the ultra-precision machine is moved up and down (Figure 2b, 1.), while the current distance of the tool shank to the capacitive displacement sensor was determined at the reversal points (Figure 2b, 2.). Using these distance values, the calculated angle can be compensated by the C-axis of the ultra-precision machine (Figure 2b, 3.). This allowed the angle of the tool shank to be precisely set with a deviation of ≤ 0.1°.

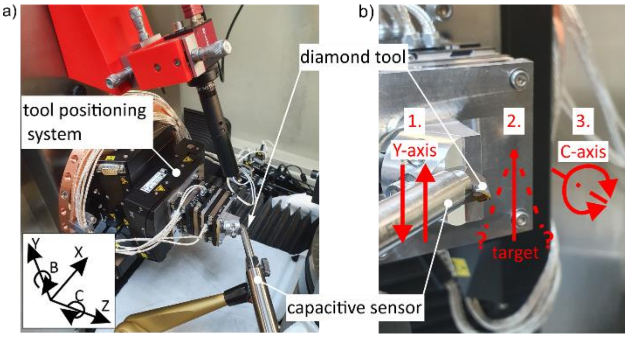

Figure 2. Measuring setup for determining and compensating the tool clearance angle.

3.2. XYZ position

The alignment of the XYZ-position of the TCP has been divided into several steps. First, the Z-position is set up. Then the XY-offset of the TCP with respect to the rotational axis of the C-axis is coarsely set. Finally, the XYZ-offset of the tool is precisely determined and compensated by generating test structures.

The Z-position of the TCP in the machine coordinate system was carried out by increasing the probing depth on the workpiece surface. This results in small indentations on contact. Z_0 can be calculated by referencing the actual with the anticipated number of indentations from the NC-program. Figure 3 shows the generated indentations at different goniometer angle positions in a scanning electron microscope (SEM) image. An adjustment of the Z-position is reliably possible by this method. However, Figure 3 also shows that after successfully setting all tool positions and angles, the Z-position should be checked again due to possible changes in the Z_0 position.

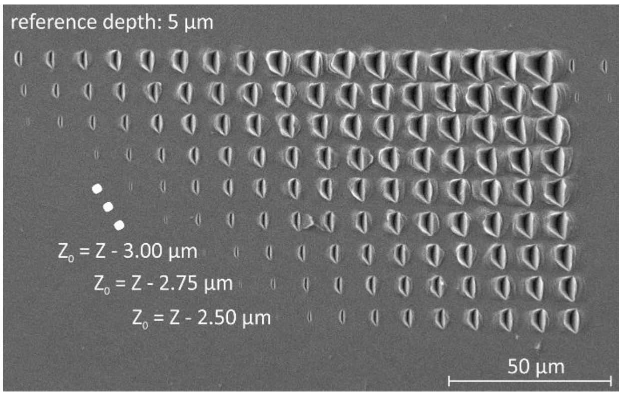

Figure 3. Indentations generated to measure the tool Z position for different goniometer angular positions.

The displacement of the TCP in the XY-plane during a rotation around the C-axis can be determined using special reference structures. Despite the fact that this method of setup was sufficient for the previous DMC kinematics, it turned out that the deviations are not distributed evenly over the angle of rotation of the C-axis. However, for a rough compensation of the TCP displacement, this method is fast and reliable. Therefore, it was applied for the two angular positions of the C-axis at 0° and 180°. The generated structures can then be recorded via a SEM and evaluated by image processing in MATLAB®. For compensation, the determined position deviations are compensated through the X'- and Y'-axes of the tool positioning system. Figure 4 shows two reference structures which in a) still show a deviation in the XY-plane and in b) show deviations below 1 µm. reaching this order of alignment precision, the next step of the tool alignment process commences.

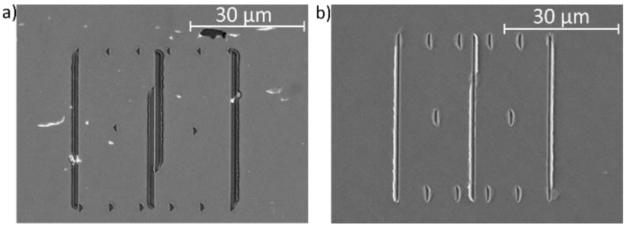

Figure 4. Reference structures for setting up the tool position in the XY plane.

For fine adjustment of the XYZ-offset, a compensation matrix was implemented in the CAD/CAM system for the specific angular positions of the C-axis for generating retroreflector arrays, i.e. three-sided cavities with facets oriented at 0°, 120° and 240°. The same program was used as for setting up the Z_0-position, but with Y-offsets of 20 µm between each C-orientation to avoid overlaps. This results is depicted in the following Figure 5.

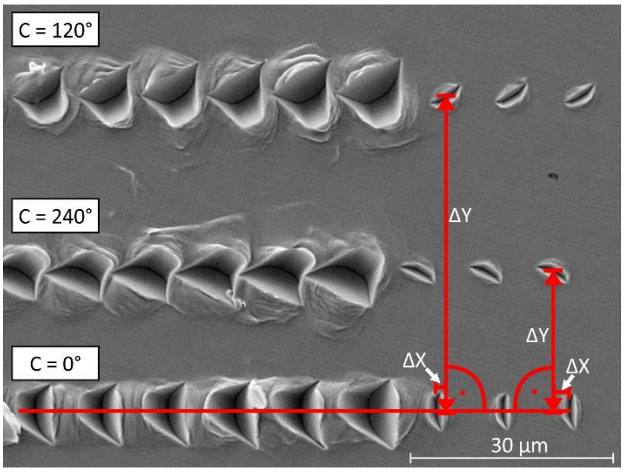

Figure 5. Measurement of the XYZ-deviations by image processing in MATLAB® at the generated structures.

With the SEM image shown in Figure 5, the XYZ-offset can be measured relatively from 0° to 240° and 120° by image processing in MATLAB®. Due to the known values from the CAD/CAM program, the deviations are directly taken into account in the NC-code generation and considered in the position calculation of the tool path. Achieving a deviation of < 2 µm the next step in the setup process was started, in which the ultrafine adjustment of the XY-offset was determined via individually cut cavities.

The offset for the relative displacement in the XY-plane was determined at the corner points of a machined three sided cavity for the angular positions 0°, 120° and 240°. The offset of C = 240° in relation to C = 0° is shown in Figure 6a and the offset of C = 120° in relation to C = 0° in Figure 6b.

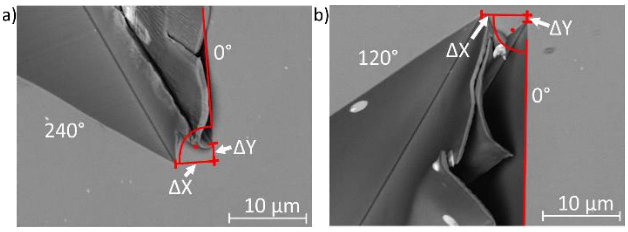

Figure 6. Measurement of the XY deviations at generated cavities.

In order to achieve an optimal result in the final retroreflector array and to avoid any chips in the cavity, a slight overlap of the corner points is intended and ensures that the chip is released and the highest possible lighting efficiency achieved. Therefore, also this part of the setup had to be done iteratively until a sufficient accuracy in the tool positioning was achieved. Once a tool positioning deviation of < 0.5 µm was detected, a small retroreflector array was machined and used to measure the structure angle along the outer facet surfaces in relation to the top surface.

3.3. Structure angle

The structure angle is determined via the lateral and vertical extent of the facets. Because the uncertainty of the angle directly relates to the size of the facet, the longest possible distance should be used in this case. In this context, it was found that the structure angle can only be reliably determined on the basis of generated cavities with at least 500 µm width. A 3D laser scanning microscope (Keyence VK-X1000) was used, which is able to measure the steep sides of the optically reflecting facet surfaces.

Nevertheless, the measurements of the structure angle still showed a deviation of ± 0.1°. Thus, several test structures were measured to calculate a mean value of the predominant structure angle.

Afterwards, the resulting angle was compared with the nominal value and a compensation was performed using the goniometers.

4. Machining experiments and results

After the tool positioning setup was completed, two retroreflector arrays were machined at different positions in the working space. The centres of the retroreflector arrays to be cut were shifted in the X-axis by 54 mm and in the Y-axis by 102 mm from Figure 7a to Figure 7b.

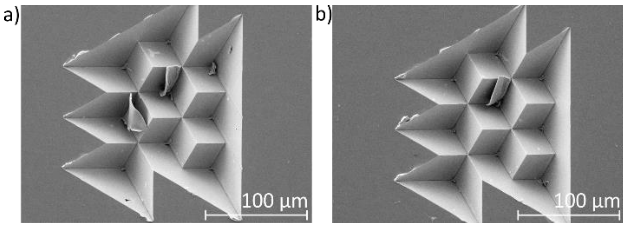

Figure 7. Machined retroreflector arrays with a centre of the arrays at a) X = 0 mm; Y = 0 mm and b) X = 54 mm; Y = 102 mm.

The generated retroreflector arrays show a consistent manufacturing quality at both positions (see Figure 7). The facet surfaces are formed correctly and only few residual chips can be seen. This can be compensated by a further iteration of the fine adjustment of the XYZ-offset. The spanned working space of the arrays shown in Figure 7 corresponds to a theoretically structurable area of 5,508 mm² and thus significantly exceeds the previously structurable areas of max. 900 mm². With this promising result, a final validation was started by cutting large-area retroreflector arrays into a mould insert.

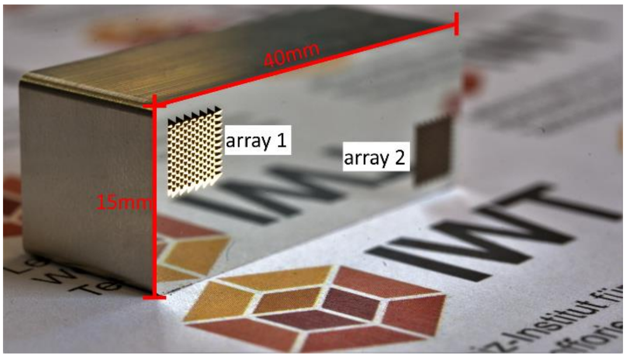

Figure 8. Machined mould insert with two cut micro-retroreflector arrays á 5x5 mm².

Two retroreflector arrays with a structure width of 250 µm and an area of 5x5 mm² each, were cut at the outer areas of the mould insert. Figure 8 shows the manufactured mould insert made of nickel silver. The cutting process of the array 1 and 2 from Figure 8 was carried out in one workpiece clamping. The arrays were cut consecutively with the same tool and identical NC program. The only difference between the arrays is their diverging position in the working space.

The difference in manufacturing quality of both arrays is negligible. Figure 9 shows an SEM image of the generated retroreflector array 1. On the facet surfaces, some minor defects are visible at the outer edges. These defects are only visible at the outer edges because they have been removed within the optical surface during machining. The defects are located exactly at the edge from one side of the corner cube to the other and could indicate that the diamond tool alignment was not yet optimised.

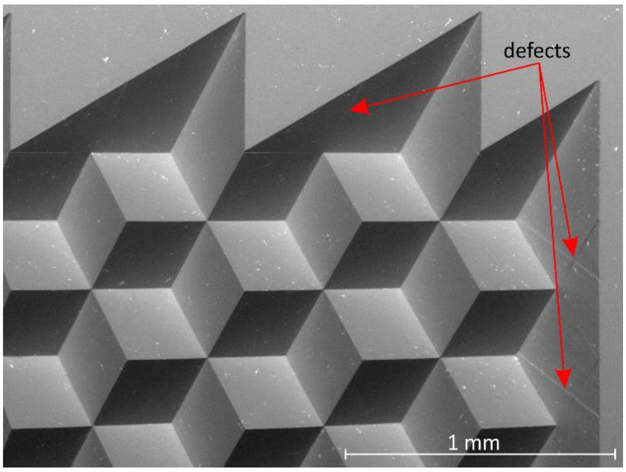

Figure 9. SEM image of the generated retroreflector array in area 1 at 100x magnification.

A closer look at the facet surfaces in Figure 10 indicates a slight waviness on the optical functional surfaces. This waviness probably is the result of instabilities in the machining process. Due to the stacking of several axes on the air-bearing main spindle, a displacement of the tool tip can occur even with cutting forces in the 1 Newton range or below. Additionally, low stiffness of the experimental setup could have led to a stick-slip effect, resulting in a wavy pattern. The actively controlled piezo linear actuators could also have had an influence on the generated structures.

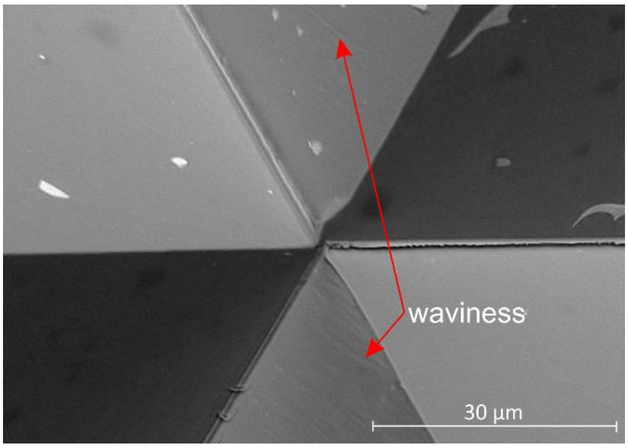

Figure 10. SEM image of the generated retroreflector array in area 1 at 3000x magnification.

5. Summary and outlook

It has been successfully demonstrated that a multi-axis tool positioning system can be used in a complex ultra-precision machining process. For a safe and precise tool alignment, the tool position was detected with several tactile, optical and capacitive measuring systems, either directly or via reference structures, and subsequently compensated by the multi-axis tool positioning system. The detection of the structure angle has turned out to be a major challenge, as this could only be detected with a laser confocal microscope due to the reflexivity and slope of the surfaces. However, it has been shown that this measuring method requires further testing with alternative measuring equipment in order to obtain a reliable measured value. The general tool position in the spatial directions X, Y and Z, could be sufficiently determined by image analysis of pictures from a scanning electron microscope and compensated for by the linear axes to < 250 nm position deviation. The results of the new machining kinematics demonstrate that the use of the new tool positioning system in the production of discontinuous microstructures, using retroreflector arrays as an example, made it possible to increase the structurable area in the working space of the ultraprecision machine by more than 500 %.

To investigate the defects in the optical facet surfaces, stiffness investigations will be carried out in future work. In addition, it will be investigated how a reduction of the actively controlled additional axes contributes to an improved manufacturing quality. Furthermore, the production of several mould inserts distributed in the entire workspace is planned in order to prove the production quality of the new process kinematics qualitatively and quantitatively. Finally, extensive examinations of the optical performance mould inserts will be conducted.

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