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Diamond Micro Chiseling of large-scale retroreflective arrays

Ekkard Brinksmeier, Ralf Gläbe, Lars Schönemann*

LFM – Laboratory for Precision Machining, Badgasteiner Straße 2, 28359 Bremen, Germany

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ABSTRACT

Triple mirror retroreflectors are essential components for safety applications, communications and measurement equipment. While downscaling of characteristic dimension is possible for triangular retroreflectors, this is a challenging task for full-cube retroreflectors, due to the absence of continuous tool paths. Thus, the Diamond Micro Chiseling (DMC) process has been developed which allows the machining of full-cube retroreflectors by overlapping a series of sharp-edged pyramidal microcavities. In the past, this has been successfully demonstrated on a small-scale up to 3 mm × 3 mm with a structure size of 150 μm. Industrial applications, however, require the structuring of areas which are significantly larger than 10 mm × 10 mm.

This paper will introduce the technology for machining such pattern with the help of the DMC process. Particular attention will be given to the measurement procedures and required tolerances for performing an in situ tool change as well as the optimization strategies for reducing the required process time.

1. Introduction

The manufacture of microstructures has been in focus of many recent research projects, as they can be used to enhance technical surfaces with all kinds of additional functionalities [1–3] and thus are driving advances in many fields of application [4–6].

A special type of optical structures is retroreflective surfaces which act as functional features for safety applications [7], communications [8] and measurement [9] equipment. They can be manufactured as a combination of lens and mirror (cat's-eye retroreflector) or in the form of triple mirrors with perpendicular facets (cube corners) [10]. Lens and mirror reflectors are mainly used in security applications because they offer a greater acceptance angle of the incident light. Triple mirror structures are preferred in measurement applications, as a smaller amount of the incident light is lost due to scattering effects [11]. In most applications, multiple of these structures are combined in an array to form a retroreflecting surface. According to the geometry of the mirror facets, it is distinguished between retroreflectors with triangular (i.e. triangular facets) or hexagonal (i.e. cubic facets) aperture. Other types of triple mirror retroreflectors (e.g. polyhedrons [12]) are also sometimes used to improve the retroreflective performance, but are comparatively uncommon. In this paper, the term hexagonal or triangular retroreflector describes an array of the abovementioned triple mirror structures.

Smaller structures result in a lower parallel displacement of the reflected light and thereby allow smaller measurement devices and improved performance. Reducing the structure size of hexagonal retroreflectors is of particular interest, as they provide 100% efficiency at 0° incidence compared to approximately 66% with triangular retroreflectors (see Fig. 1) [13]. Furthermore, when replicating an array of miniaturized structures on reflective foils, the retroreflective surface can be bent without loss of optical function and thus offer a broader range of applications.

Another important factor in machining highly efficient hexagonal retroreflectors is the angular accuracy between the mirror facets. A maximum deviation of 0.05° is demanded in the patent of Stamm [15] for automotive applications, while the deviations for free space communication systems are extensively discussed by Zhu et al. [16].

2. Diamond Micro Chiseling

While a downscaling of structure size is possible for arrays of triangular retroreflectors using diamond milling [14,17] or grooving [18] processes, this is a challenging task for hexagonal retroreflector arrays, due to the absence of continuous tool paths, as the commonly used pin-building techniques are not applicable. In this case, the concave sharp edges cannot be machined by processes based on rotational motions (e.g. turning or milling) [19]. Thus, the Diamond Micro Chiseling (DMC) process has been developed, for machining arbitrary prismatic microcavities of which miniaturized hexagonal retroreflector arrays in a size between 50and 500 μm [20] can be generated.

* Corresponding author. Tel.: +49 421 218 51142; fax: +49 421 218 51119.
E-mail address: schoenemann@lfm.uni-bremen.de (L. Schönemann).

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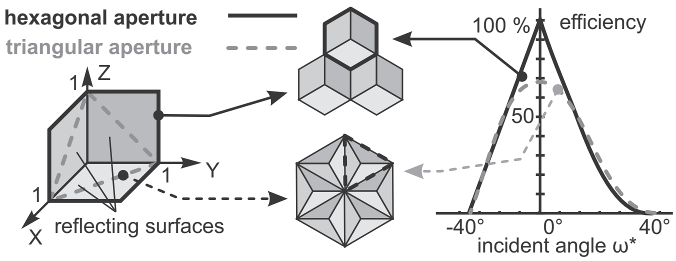

Fig. 1. Reflectivity of retroreflectors with hexagonal and triangular aperture cf. [14].

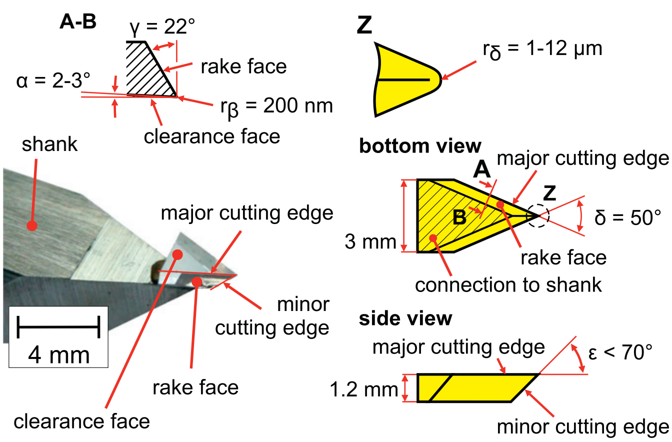

Fig. 2. V-shaped diamond tool dedicated for the Diamond Micro Chiseling process.

2.1. Tool geometry

The DMC process relies on dedicated V-shaped monocrystalline diamond tools. In comparison to conventional diamond tools used for turning or milling operations, the DMC tools are operated 90° rotated around the shaft axis while maintaining the cutting direction of conventional tools. This results in a switched alignment of rake and flank face and consequently a completely different configuration of the cutting edges and tool angles. The characteristics of the diamond tools used for Diamond Micro Chiseling are shown in Fig. 2.

While in theory a sharp edged tool is necessary for generating perfect prismatic microcavities, most tools designed for Diamond Micro Chiseling feature a rounded nose with a radius of $r_\delta = 1–12\,\mu m$ for stability reasons. Some DMC tools also feature a rounded cutting edge ($r_\beta = 200–300\,nm$), which further improves the stability of the tool and is mainly used for rough cutting purposes. In order to minimize the necessary effort for tool alignment, intrinsic rake ($\gamma = 22°$) and clearance ($\alpha = 2–3°$) angles are ground into the diamond thus only making it necessary to align certain reference planes on the shank within the machine tool. The opening angle ($\delta = 50°$) and the corner angle ($\varepsilon = 70°$) of the tool determine the machinable geometric spectrum of the microcavities. Due to the quasi-symmetric geometry of the tool, there is a certain dependency between the angles of the diamond tool. For example, decreasing the rake angle results in an enlarged corner angle and thus reduces the machinable geometric spectrum. This could be avoided by utilizing an asymmetric tool design which, however, further increases the complexity and costs of the already expensive tools.

2.2. Machine setup and process kinematics

An ultraprecision machine tool with at least five numerically controlled axes (three linear and two rotational) is required for the Diamond Micro Chiseling process (Fig. 3).

One of the rotational axes (B) is used for setting the inclination angle (χ) of the tool relative to the workpiece, while the second one (C) is used to rotate the workpiece itself. The linear axes (X, Y and Z) are used for positioning the tool relative to the workpiece and for executing the cutting motion.

In the first step, the tool plunges into the surface in [$-XY-Z$] direction until the apex of the cavity is reached and is then retracted from the surface in [XYZ] direction (see Fig. 4). Hence, a single mirror facet with triangular geometry is generated which has an inclination angle equal to χ. For cutting the next facet, the workpiece has to be rotated and the tool repositioned to the endpoint of the previous cut. This procedure is continued until the starting point of the first cut is reached and the chip is separated from the cavity. To minimize the stress on the diamond tool, the structures have to be cut in several layers with constant chip thickness [21]. Therefore, a stack of identical cavities is machined with decreasing offset in Z direction.

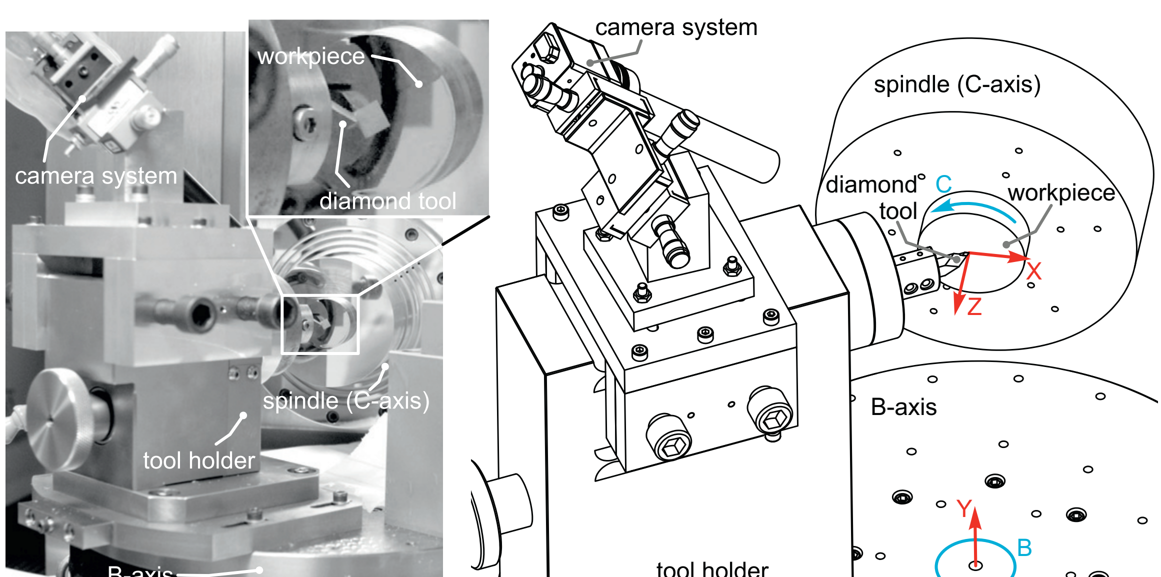

Fig. 3. Machine setup for Diamond Micro Chiseling on a Nanotech 350FG (left: photography of setup, right: schematic wireframe image).