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Review

Review on diamond-machining processes for the generation of functional surface structures

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ABSTRACT

In this paper, technologies used for the generation of functional surface structures for optical applications will be reviewed and two novel processes introduced. In many cases, these structures are generated by diamond machining processes into mold inserts for replication purposes or for direct application as metal optics. However, the spectrum of machinable structures is limited by the applied kinematics and tool shapes. For example, the generation of pyramidal prismatic structures with sharp edges is not possible. In order to extend the spectrum of machinable geometries, novel processes like Diamond Micro Chiseling (DMC) or nano Fast Tool Servo (nFTS) assisted turning, have been developed.

Contents

1. Introduction

Micro- and nanostructures are essential components for enhancing technical surfaces with specific functionalities, such as improved aerodynamic behavior [1], tribological performance [2] or information storage [3]. In optical components, functional surface structures are key elements for a variety of innovative applications and tend to have a large impact on the economic relevance of these products [4–6].

In the beginning, the development of optics and optical systems was limited to the machining of continuous surfaces. Lately, due to a high demand for components with an extended functionality, structured surfaces are of increasing importance. Their field of application is manifold: reflective or refractive structures are used

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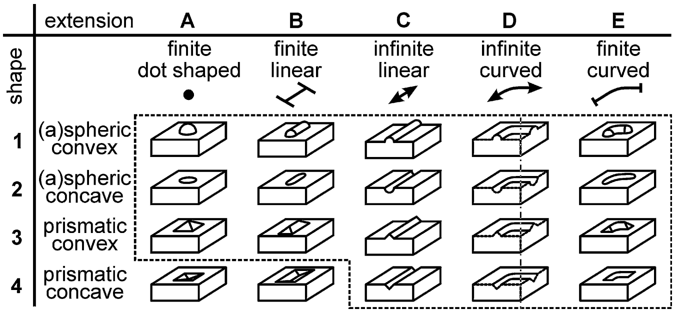

Fig. 1. Classification of microstructures by shape and extension.

for automotive illumination systems [7], light distribution in TFT panels [8] or as reflective foils for traffic signs or safety garments [9], while diffractive structures are used e.g. for the correction of the chromatic aberration [10] or for security applications [11].

In this context, diamond machining is a key process. Being able to generate surface roughness of only a few nanometers and form accuracies in the sub-micrometer range, it offers considerably more degrees of freedom than other mechanical/chemical processes [12]. Furthermore, a single machine tool, which incorporates up to five controlled axes, is applicable for machining a variety of different geometries (see Fig. 1), thus enabling the economic fabrication of small volumes or even single pieces. Most geometric shapes are machinable as negatives and used for molding inserts for direct replication in batch production environments [13].

Fig. 1 classifies microstructures according to their shape and lateral extension, with each pictogram exemplary standing for a class of geometries. The type of extension covers the length (dot shaped, finite, infinite) as well as the form (linear, curved, square/prismatic) of the extension. The shape of a structure is distinguished between (a) spherical and V-shaped (prismatic) geometry and can either be convex or concave.

Dot shaped, in this case, stands for singular elements, like lenslets or pyramidal structures, while 'finite' means that the structures have geometrically defined start and endpoints. For structures which span over the entire workpiece area or feature closed cutting paths, the term 'infinite' is used.

Diamond turning and diamond milling are standard processes, allowing the machining of rotational (type D) and linear (type C) structures. In case of diamond turning, the process can be extended by an additional Fast or Slow Tool Servo, increasing the machinable geometry spectrum within specific limits (E2 and E4). Regardless of the high flexibility of these processes, the realization of certain geometries, like pyramidal micro cavities with sharp edges (A4 and B4) or arbitrary diffractive structures with high information density, is a challenging task.

In the following, standard diamond machining processes will be reviewed and two novel processes, which extend the spectrum of machinable geometries considerably, will be introduced.

2. Review on standard structuring processes

2.1. Diamond turning

Diamond turning processes generate the cutting motion by the rotation of the workpiece, while the tool is guided in relation to the surface, thereby copying the geometry of the diamond tool into the surface to determine the shape of the desired part. In the most basic setup, only two controlled axes (for generating the feed and infeed motion) and a spindle are necessary for the generation of rotationally symmetric (type D) structures, like Fresnel lenses. The shape of the structure is either determined by the geometry of the diamond tool (profile turning) or by the modulation of the infeed depth (form-turning). Profile turning can generate circular or spiral-type structures by plunging the diamond tool into the surface according to the radial position of the tool on the surface (Fig. 2a) or by superposition of the tool geometry and the applied feedrate (Fig. 2b). More complex shapes can be generated easily when contouring the desired shape by controlling both linear axes (Fig. 2c).

If the cutting depth is dynamically modulated according to the radial and angular position on the surface, structures without rotational symmetry (type E) can be realized in turning operations (Fig. 2d). Depending on the frequency of the modulation and the applied device, these processes are called slow slide or Fast Tool Servo turning.

Examples for diamond turned functional surfaces include Fresnel lenses [14], or in case of Fast Tool Servo turning, facetted mirrors and microlens arrays [15].

The inherent advantage of turning operations is the high machining speed, as for a fixed characteristic structure dimension the process time is only scaling linearly depending on the diameter of the workpiece.

2.2. Diamond milling

In ultraprecise milling processes, a monocrystalline diamond tool is rotating on a spindle and moved in relation to a fixed workpiece. Using at least three numerically controlled axes, nearly any surface shape may be machined in optical quality. According to the chosen configuration, these processes are divided into face- and peripheral-milling, as it is shown in Fig. 3. In face milling operations, the tool is rotating along an axis perpendicular to the workpiece, whereas in peripheral milling the rotational axis is parallel to the machined surface.

For the generation of plane, spherical, aspherical or freeform surfaces, both peripheral- and face-milling is used. The obtainable kinematic roughness is directly dependent on the corner radius R_ε and, in the case of peripheral milling, also the swing radius R_{swing} of the diamond tools. Thus, peripheral milling is faster than face milling when machining surfaces of the same size when $R_{swing} \gg R_\varepsilon$. On the other hand, face milling is preferred when generating freeform surfaces, as the curvature and slope angle are not limited by the swing radius.

As the geometry of a cutting edge is directly copied into the workpiece, nearly any kind of groove-like structure (type C) are machinable by peripheral milling in combination with profiled, V-shaped or trapezoidal cutting tools. By intersecting multiple of these grooves, even prismatic features (types A3 and B3) may be generated. In order to do this, a rotational axis has to be mounted

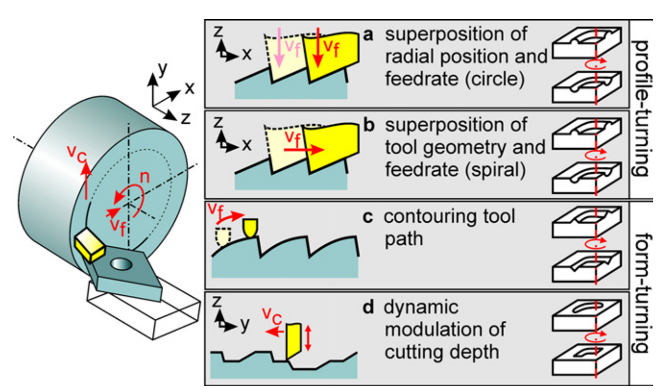

Fig. 2. Structure generation in diamond turning.