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Theoretical and experimental investigation on the novel end-fly-cutting-servo diamond machining of hierarchical micro-nanostructures

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ABSTRACT

By combining the concepts of fast/slow tool servo and fly cutting, a novel end-fly-cutting-servo (EFCS) system with four-axis motions is proposed for deterministic generation of hierarchical micro-nanostructures, which are conventionally difficult for both mechanical and non-mechanical methods to achieve. In the EFCS system, an intricately shaped primary surface is generated by material removal, while the desired secondary nanostructure is simultaneously constructed using residual tool marks by actively controlling the tool loci. The optimal toolpath determination strategy, as well as surface generation algorithm for the EFCS system, has been developed with consideration of geometries and installation poses of the diamond tool. Numerical simulation of surface generation is conducted to demonstrate the effectiveness of the novel machining method and features of the obtained hierarchical structures. A nanostructured micro-aspheric array and a nanostructured F-theta freeform surface are successfully fabricated in experiments. This research provides a very promising technique for the generation of hierarchical micro-nanostructures to realize performance integration of artificial components.

1. Introduction

Mimicking bio-surfaces featured hierarchical micro-nanoarchitectures leads to inconceivable impacts on optical, mechanical, frictional, biological, and interfacial properties of artificial components in current industries [1–3]. For instance, the nanostructures on the micro-lens array make the array not only suitable for optical imaging but also for antireflective and hydrophobicity applications [4], and the phase gratings on freeform optics can construct the hybrid micro-optics comprising refractive/reflective freeform and high-frequency diffractive structures for function integration of the optical system [5]. To popularize practical applications of the bio-inspired surfaces, a variety of machining methods have been developed which can be classified, according to structure formation modality, into additive and subtractive processes. The additive process is predominated by two-photon polymerization and self-assembly [6–8], and the subtractive process can be subdivided according to material removal nature into physical, chemical, and mechanical [3,4,9,10]. The additive as well as the physical and chemical processes is commonly restricted with respect to specified materials and long processing times. In addition, it is often hard for a majority of these methods to generate complicated structures with high form accuracy.

Mechanical machining including cutting and abrasive machining is more universal and deterministic due to the capacity of generating intricate surfaces with submicron form accuracy and nano-metric roughness on a variety of engineering materials [9]. Recently, diamond cutting was introduced for this purpose and found to be very promising for deterministic generation of hierarchical surfaces. In diamond cutting, by means of fast tool servo (FTS) or slow tool servo (STS), true three-dimensional (3D) artificial compound eyes (ACEs) can be well generated [11–13]. With the 3D ACEs, the primary surface was spherical with a small curvature, and imposition of secondary micro-prism arrays as well as micro-sphere arrays on the primary curved surface were

Abbreviations: EFCS, end-fly-cutting-servo; FTS, fast tool servo; STS, slow tool servo; 3D, three dimensional; ACE, artificial compound eye; EVT, elliptical vibration texturing; RUT, rotary ultrasonic texturing; RTM, residual tool mark; PDS, primary desired surface; VCM, vertical cutting mode; HCM, horizontal cutting mode; CLP, cutter location point; CCP, cutter contact point; MAA-NP, micro-aspheric array with nano-pyramids; FFS-NP, F-theta freeform surface with nano-pyramids; CNC, computer numerical control

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Nomenclature

o_s–$x_s y_s z_s$ Cartesian coordinate system on the spindle axis
o_w–$x_w y_w z_w$ Cartesian coordinate system of the workpiece
o_t–$x_t y_t z_t$ Cartesian coordinate system of the CLP of the diamond tool
h, w length and width of the workpiece
R_d rotation radius of the diamond tool
v relative cutting speed
α angle discrepancy
R_T nose radius of the diamond tool
γ_0 rake angle of the diamond tool
θ cutting angle of the diamond tool
θ_{min}, θ_{max} the lower and upper angle boundary of the cutting angle
ρ polar axis
$\varphi_{k,l}$ azimuth of the l-th CLP in the k-th revolution
N_s the number of discrete CLP per revolution
f_x, f_y feedrate per revolution along the X- and Y-axis directions
(x_T, y_T, z_T) coordinate position of the point at the cutting edge
$\left(x_{axis}^{(k,l)}, y_{axis}^{(k,l)}\right)$ planar coordinate position of the spindle axis
(x_w, y_w, z_w) coordinate position of the point at the PDS
$\left(x_{CLP}^{(k,l)}, y_{CLP}^{(k,l)}, z_{CLP}^{(k,l)}\right)$ coordinate position of the l-th CLP in the k-th revolution
$z_s^{(k,l)}$ axial position of the cutting edge projected on the PDS
z_0 initial axial position of the CLP
$S_w(\cdot)$ mathematical law for the PDS
N_s the number of subdivided pieces between any two successive CLPs
ζ_x, ζ_y meshing resolutions along the x- and y-axis directions
$S_{m,n}$, $P_{m,n}$ grid node and the corresponding CLP passing through it
$(x_m^G, y_n^G, z_{m,n}^G)$ coordinate position of the grid node $S_{m,n}$
$O_1(j)=(x_1(j),y_1(j))$ lower boundary point of the j-th piece
$O_2(j)=(x_2(j),y_2(j))$ upper boundary point of the j-th piece
φ_j azimuth of the j-th piece
$\varphi_{m,n}^D$ azimuth position of the piece passing the grid node $S_{m,n}$
$z_{m,n}^D$ axial position of the CLP passing the grid node $S_{m,n}$
$T_1 = \left(x_1^D, y_1^D\right)$ lower boundary point of the piece with respect to $\varphi_{m,n}^D$
$T_2 = \left(x_2^D, y_2^D\right)$ upper boundary point of the piece with respect to $\varphi_{m,n}^D$
a, b, c control parameters for the F-theta surface
k, R_0, C, s control parameters for the aspheric structure

generated by freeform machining. The main advantage of the FTS/STS is the capacity of processing well-defined structures with ultra-fine accuracy. Taking the 3D ACE with micro-lens array on a steep curved surface for instance, a form error less than 6 μm (PV) and roughness less than 5 nm (rms) can be well achieved [13]. The limitation of FTS/STS is that the periodicity of secondary structures generated by FTS/STS is commonly in an order of several hundred micrometers, and it is hard to obtain structures with much smaller scales due to the limitation of moving bandwidth of the mechatronic actuation system. Although the recently developed nano-FTS was capable of generating complex nanostructures, it was insufficient for large area fabrication of curved structures due to rapid tool wear and sub-micrometer stroke with limited working bandwidth [14,15].

To obtain much smaller scales of the secondary structures, the ultrasonic elliptical vibration texturing (EVT) method was recently introduced, and a set of micro-dimple patterns on a cylindrical surface were generated [16,17]. Essentially, it could only be regarded as flat surface texturing from the view of cylindrical cutting. Furthermore, textured micro-channels with hierarchical structures were achieved by adopting the EVT method to enhance the anisotropic wettability [18]. The residual cusp derived from two successive ellipses of the loci was served as the secondary texture, and the amplitude and wavelength of that was about 0.5 μm and 5 μm, respectively. In Ref. [19], a rotary ultrasonic texturing (RUT) combining ultrasonic vibration and rotation of a one-point diamond tool was proposed to obtain 2.5D microstructures with an imposition of wavy nanostructures on flat surface. The amplitude and wavelength of the nanostructure was about 50 nm and 2.5 μm, respectively. By changing machining parameters, some specified patterns were well obtained. Both EVT and RUT are very promising for surface patterning due to its high efficiency and low dimensional scale, with both being induced by ultrasonic vibrations. However, they are sufficient for flat surfaces but difficult for intricate surfaces with freeform or even structured features.

As discussed above, it is still a challenge for both mechanical and non-mechanical machining methods to flexibly generate hierarchical micro-nanostructures which are composed typically of a secondary nanostructures superposed on a primary microstructures. Motivated by this, a novel single point diamond cutting method, as the end-fly-cutting-servo system, is proposed in the present study to generate complicated freeform surfaces with imposition of secondary nanostructures, combining the concepts of FTS/STS and fly cutting. In the EFCS system, the material removal is employed to form the primary surface, and the residual tool marks (RTMs) are actively controlled to form the secondary nanostructures. By deliberately choosing tool geometry, tool loci, and cutting parameters, complicated hierarchical micro-nanostructures with different shapes and dimensional sizes can be obtained.

2. The end-fly-cutting-servo system

The concepts of FTS/STS and fly cutting are synthesized to complement each other, resulting in the novel EFCS system with enhanced machining capacity. In the following, details of the basic principle, the system configuration and the processing characteristics are presented.

2.1. Basic principle

In mechanical machining, the relative motions between the diamond tool and the workpiece finally determine the shape and the micro-topography of the machined surface. On this basis, the required motions for the structure generation are reallocated to the four-axis servo motions of the ultra-precision machine tool.

To generate sharp-edged structures, intersections of the tool loci on the workpiece are required. In conventional FTS/STS, the cutting is operated in the Cylindrical coordinate system, where the cutting direction is always perpendicular to the polar axis of the workpiece. It is impossible to construct the intersections of the cutting loci. With the EFCS, the diamond tool is installed on the spindle and rotates with it, whereas the workpiece is clamped on the slide. By exchanging the positions of the diamond tool and the workpiece, the operation in EFCS is transferred to the Cartesian coordinate system. Thus, a variety of cutting directions could be