CIRP Annals - Manufacturing Technology 64 (2015) 133–136

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Novel end-fly-cutting-servo system for deterministic generation of hierarchical micro–nanostructures

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ARTICLE INFO

Keywords:
Ultra precision
Cutting
Micromachining
Nanostructure

ABSTRACT

This paper reports on the diamond cutting based generation of hierarchical micro–nanostructures, which are conventionally difficult for both mechanical and non-mechanical methods to achieve. A novel end-fly-cutting-servo (EFCS) system, with four-axis servo motions that combine the concepts of fast/slow tool servo and end-face fly-cutting, is proposed and investigated. In the EFCS system, an intricately shaped primary surface is generated by material removal, while the desired secondary nanostructures are simultaneously constructed using residual tool marks by actively controlling tool loci. The potential of the EFCS system is demonstrated firstly by fabricating a nanostructured F-theta freeform surface and a nanostructured micro-aspheric array.

1. Introduction

Mimicking bio-surface featuring hierarchical micro–nano architecture leads to inconceivable impacts on optical, mechanical, frictional, biological, and interfacial properties of artificial components [1,2]. Currently, a variety of machining methods have been established for generating the multi-scale surfaces, including soft lithography, self-assembly, soft nano-imprinting, laser based two photon polymerization, reactive-ion and laser etching, chemical synthesis and electrochemical processing [2–4]. However, these methods are commonly restricted with respect to specified material, long processing time, complex operations and expensive costs. Besides, it is still a crucial task for a major of them to flexibly generate hierarchical micro–nanostructures with an accurate primary complicated surface and an ordered secondary nanostructure [3,4].

Mechanical machining, especially diamond cutting, is widely regarded as more universal and deterministic due to the capacity of generating intricate surfaces with submicron form accuracy and nanometric surface roughness on a wide spectrum of engineering materials. By means of fast tool servo (FTS) or slow tool servo (STS), hierarchical macro–microstructures can be well obtained; for example, the true three dimensional (3D) artificial compound eyes [5,6]. The scale of obtained secondary structures is often limited to an order of several hundred micrometres, and it is also hard to generate discontinuous structures with very sharp edges due to its limited dynamic response. Although the recently developed nano-FTS could fabricate very complicated nano-structures, the nano-level stroke and finite bandwidth restrict its applications in obtaining large-area hierarchical structures [7]. Another diamond cutting method, namely the fly-cutting, is very promising for the generation of sharp-edged structures [8]. However, it is often of extremely low efficiency and is limited to flat primary surfaces.

To obtain much smaller scales of secondary structures, ultrasonic elliptical vibration texturing (UEVT) method was proposed to generate micro-dimple patterns and textured micro-channels [9,10]. Another rotary ultrasonic texturing (RUT) method, combining rotation and ultrasonic vibration of a one-point diamond tool, was developed to obtain micro-grooves with imposition of wavy nanostructures [11]. Both UEVT and RUT are promising for surface patterning due to the high efficiency and low dimensional scale, with both being induced by ultrasonic vibrations. However, they are sufficient for flat surfaces but are difficult for processing intricately shaped primary surfaces.

As discussed above, it is still a challenge for both mechanical and non-mechanical processes to flexibly generate hierarchical micro–nanostructures. In this study, a novel end-fly-cutting-servo (EFCS) system combining the concepts of FTS/STS and fly-cutting is proposed for the generation of the multi-scale structures.

2. End-fly-cutting-servo system

The concepts of FTS/STS and end-face fly-cutting are synthesized to complement each other, resulting in the novel EFCS system with enhanced machining capacity. In the following, details of its basic principle, system configuration, and surface generation mechanism are presented.

2.1. Basic principle of the EFCS system

In diamond cutting, relative motion between the diamond tool and the workpiece finally determines the shape of machined surface. On this basis, the required motion for generating the

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http://dx.doi.org/10.1016/j.cirp.2015.04.082
0007-8506/© 2015 CIRP.

unique structures is identified and reallocated to the four-axis servo motions of the ultra-precision machine tool.

To generate sharp-edged structures, intersection of the tool loci over the workpiece is adopted. In FTS/STS turning, it is operated in the cylindrical coordinate system, where the cutting direction is always perpendicular to the polar axis of the workpiece. Thus, it is impossible to construct the intersections. With the EFCS system, the diamond tool is installed on the spindle and rotated with it; meanwhile, the workpiece is clamped on the slide. Essentially, the cutting operation is transferred to the Cartesian coordinate system. Thus, a variety of relative cutting directions can be obtained with respect to the workpiece due to the circular motion of the diamond tool.

Translational servo motions along the *Z*-axis of the machine tool were inherited from FTS/STS and rearranged at the workpiece to be responsible for deterministic generation of the intricately shaped primary surfaces. Simultaneously, side feeding along the direction approximately perpendicular to the cutting direction is adopted to make the material removal cover the whole workpiece. Overall, two different kinds of surface generation mechanisms are adopted in the EFCS system: the primary desired surface (PDS) is formed by material removal, just as in conventional cutting; while the secondary nanostructures are constructed by means of actively controlling the residual tool marks (RTM).

2.2. Configuration of the EFCS system

Fig. 1(a) illustrates the configuration of the EFCS system, which consists of four-axis servo motions, namely *X*-, *Y*-, *Z*- and *C*-axis. The diamond tool is installed on the fixture and then attached on the spindle. The workpiece is clamped on the slide and follows the translational servo motions along the *Z*-axis to generate the intricately shaped PDS. Taking advantage of the *X*- and *Y*-axis, relative positions between the spindle axis $o_s z_s$ and the workpiece can be adjusted, resulting in a variety of relative cutting directions as shown in Fig. 1(b). By combining these directions, a variety of intersection modes of the cutting loci can be obtained, accordingly generating arbitrary polyhedron nanostructures on the well-defined PDS. As discussed above, side feeding along the directions shown in Fig. 1(b) should be adopted to cover the whole surface, which also requires cooperation of the two servo motions along the *X*- and *Y*-axis. Considering the rotations of the diamond tool (*C*-axis), the EFCS system is essentially a four-axis motion assisted diamond cutting.

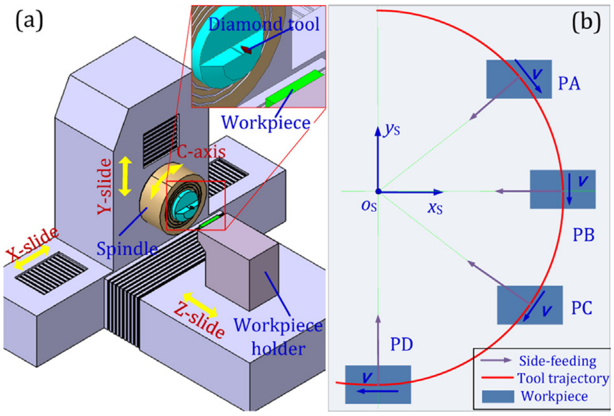

Fig. 1. Configuration of (a) the EFCS system and (b) the induced cutting modes, where o_s–$x_s y_s$ denotes the coordinate system fixed on the spindle axis, and *v* denotes the relative cutting speed.

2.3. Secondary nanostructure generation in the EFCS system

Since the generation of the PDS in the EFCS system follows the principle of FTS/STS, only the mechanism for the secondary nanostructures, especially the typical nano-pyramids, is detailed here. To fabricate the nano-pyramids, two cutting directions at the positions *PB* and *PD* as shown in Fig. 1(b) are employed, which corresponds to the vertical and horizontal cutting modes (VCM & HCM), respectively. Further illustration of the two modes is presented in Fig. 2. If the distance between the spindle axis and the O_w–$X_w Z_w$ plane is kept as $h/2$ during cutting, it forms the VCM. If the distance between the spindle axis and the O_w–$Y_w Z_w$ plane is kept as $w/2$, it forms the HCM. With the VCM, the PDS with approximately linear RTMs along the vertical direction could be obtained. By conducting sequential cutting in the HCM, approximately orthogonal intersections of the tool loci in the two modes could result in the nano-pyramids on the PDS as illustrated in Fig. 2(b).

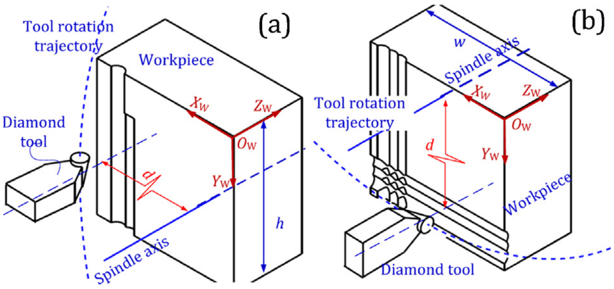

Fig. 2. Schematic of (a) the VCM and (b) the HCM, where O_w–$X_w Y_w Z_w$ is the coordinate system on the workpiece; *d* denotes the rotation radius of the diamond tool; *h* and *w* are dimensional parameters of the workpiece.

Assuming that the rotation radius of the tool is larger than the width of the cutting area, the projected tool loci along one cutting direction could be regarded as parallel arcs. Thus, with respect to the round edge of the diamond tool, analytical height and width of the RTMs at any given point can be estimated by [12]

$$h_p = \begin{cases} R_t - \sqrt{R_t^2 - 0.25\,f^2}, & \text{if}\,\rho = \infty; \\ \dfrac{\rho}{|\rho|}\sqrt{(\rho + R_t)^2 - 0.25\,f^2} - \sqrt{R_t^2 - 0.25\,f^2} - \rho, & \text{otherwise}. \end{cases} \tag{1}$$

$$d_p = \sqrt{\frac{8 h_p R_t \rho}{R_t + \rho}} \tag{2}$$

where R_t is the nose radius of the tool, *f* denotes the side feedrate per revolution, and ρ denotes the reciprocal of the local curvature of the PDS in the side-feeding direction.

As shown in Eqs. (1) and (2), the height and width of the pyramid structures are highly dependent on tool geometries, side feedrates, and local curvatures of the PDS. By deliberately choosing the cutting parameters, feature sizes of the secondary nanostructures can be actively controlled to meet the design requirements.

Taking the nano-pyramids on planar surface for example, a numerical simulation was conducted under the specified conditions presented in Fig. 3 to characterize the secondary nanostructures as well as its generation mechanism. The obtained theoretical 3D nano-pyramids and the cross-sectional profile passing the apexes are shown in Fig. 3(a) and (b), respectively. As shown in Fig. 3(b), the profile features sharp nodes and round connections, which may

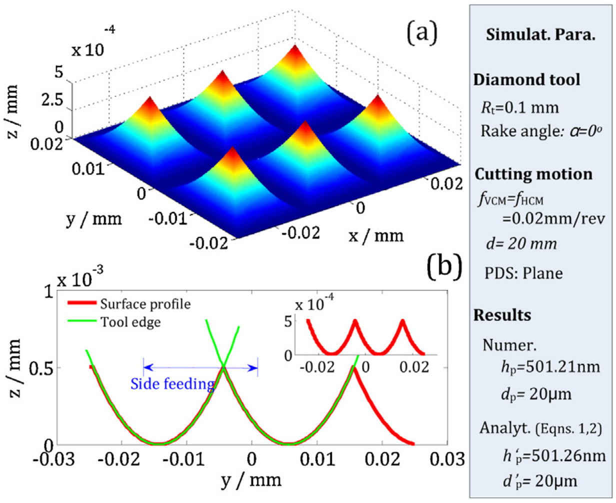

Fig. 3. Structure characteristics obtained by numerical simulation: (a) the 3D structure and (b) the 2D profile.