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Ultra-precision nano-structure fabrication by amplitude control sculpturing method in elliptical vibration cutting

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ABSTRACT

This paper studies the nano-structure fabrication on hardened steel by means of elliptical vibration cutting equipped with the ultra-precision amplitude control sculpturing method. Machining performance of the amplitude control sculpturing method is investigated, and the limitation in nano-scale machining is explored. In this proposed method, machinable part geometry is essentially restricted by vibration conditions and tool geometry. In addition, a considerable error between the amplitude command and the envelope of the tool trajectory is generated when the slope of the machining part geometry becomes steep. To overcome this error, a compensation method for the amplitude control command is proposed. In order to clarify the machining performance of the proposed technology, a series of analytical and experimental investigations are conducted. Furthermore, by applying the proposed command compensation method, nano-structures with a large ratio of structure height to wave length are machined accurately. The proposed sculpturing method is subsequently applied to the machining of nano-textured grooves and a three-dimensional grid surface, which verifies the feasibility of the proposed amplitude control sculpturing method.

1. Introduction

Micro/nano structured surfaces possess unique functions, such as hydrophobicity, low friction, and optical functions [1]. Hence, application technologies of functional surfaces with micro/nano structures have been fascinating research topics in the last few decades. In order to utilize these functional surface technologies, high performance manufacturing technology is highly required for the fabrications of micro/nano structures. Evans and Bryan [1] investigated capabilities and limitations in typical methods for micromachining such as cutting, laser machining, lithographic methods, focused ion beam (FIB) machining, and replication. Ultra-precision diamond cutting is considered to be one of the possible technologies to fabricate sophisticated micro/nano structures practically. Diamond cutting allows a high degree of freedom for structural design as compared with other methods, and thus it has been widely used especially for plastic molding applications of a variety of optical elements. Furthermore, combination of diamond cutting with fast tool servo (FTS) technology enables highly-efficient fabrication of micro/nano structures in a variety of applications [2]. It should be noted that in order to generate submicron-scale functional surfaces, Brinksmeier et al. [3] developed nano-stroke FTSes and verified feasibility of arbitrary nano structure machining of nickel silver in face turning operation. Zhou et al. [4] also succeeded in micron-scale fabrication of some diffractive optical elements made of polymethylmethacrylate (PMMA) by applying FTS technique into diamond turning.

Considering widespread use of textured surfaces applications and their mass production, manufacturing technology of functional surfaces for a variety of materials, especially for steel materials, is greatly required. Steel is a typical material that is widely used for mechanical elements and molding. However, Paul et al. [5] found that in ferrous material machining chemical affinity of materials triggers extreme chemical reaction of single crystal diamond (SCD) tools. Because of this chemical nature, conventional diamond cutting is not applicable to machining of steel due to rapid tool wear and surface deterioration [6]. Instead of diamond cutting, Brinksmeier et al. [7] applied ultra-precision grinding and abrasive polishing to fabrication of ultra-precision dies and molds made of hardened steel. High quality surface finish can be achieved successfully by those methods, while it is extremely difficult to fabricate sophisticated micro/nano-scale structures especially with sharp edges by grinding/polishing. These restrictions in conventional machining methods in fact define the bottleneck of practical use of hardened steel with functional surfaces.

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Nomenclature

$\vec{t}_e$	unit tangential vector on vibration locus
$\rightarrow t_{tar}$	unit tangential vector on target profile
$\vec{E}$	elliptical vibration vector
f_{ac}	reference frequency of amplitude control command
h_{tar}	structure height of target profile in x–z plane
h_{tarf}	structure height of target profile in y–z plane
n	counter of discrete points
v_c	nominal cutting speed
x_{cen}, z_{cen}	x, z components of a center position of elliptical vibration
x_e, z_e	x, z components of a position on elliptical vibration in x–z plane
x_{tar}, z_{tar}	x, z components of a position on target profile in x–z plane
y_{tarf}, z_{tarf}	y, z components of a position on target profile in y–z plane
α	rake angle
γ	clearance angle
ω	angular frequency of elliptical vibration
φ	phase shift of vibrations in nominal cutting direction and depth of cut direction
τ	time during elliptical vibration process
τ_n	time when tool is tangential to n-th target position
τ_s	time of tool's penetration into workpiece
ε	phase of elliptical vibration at tangential moment
λ_{tar}	wave length of sinusoidal target profile in nominal cutting direction
λ_{tarf}	wave length of sinusoidal target profile in nominal pick feed direction
λ_x, λ_y	wave lengths of sinusoidal target profile in x direction and y direction
θ_1	slope angle of target profile
θ_2	penetration angle of tool into workpiece
A_c, A_d	mean-to-peak amplitudes in nominal cutting direction and depth of cut direction
A_x, A_y	mean-to-peak amplitudes of sinusoidal target profiles in x direction and y direction
C_e	curvature of vibration locus
C_{tar}	curvature of target profile
CR_e	curvature radius of the vibration locus
CR_{tar}	curvature radius of the target profile in x–z plane
CR_{tarf}	curvature radius of the target profile in y–z plane
N	number of discrete points
O_{cen}	center position of elliptical vibration
O_e	center position of curvature of vibration locus
O_{tar}	center position of curvature of target profile
P_e	position on vibration locus
P_{tar}	position on target profile in x–z plane
R	nose radius of cutting tool

For the last few decades, ultrasonic vibration cutting technology has been successfully applied to difficult-to-cut materials machining by use of diamond tools [8]. In particular, elliptical vibration cutting (EVC) technology [9], which was proposed by Shamoto and Moriwaki, is considered as a potential candidate for the functional surface fabrication on steel materials. Moriwaki and Shamoto [10] developed primitive ultrasonic elliptical vibration cutting devices, and Shamoto and Moriwaki [11] verified the feasibility of steel material machining by use of SCD tools. By applying ultrasonic elliptical vibration during hardened steel machining, thermo-chemical reactions between diamond and steel can be suppressed significantly, resulting in successful ultra-precision machining without rapid tool wear generation and surface quality deterioration. Furthermore, Suzuki et al. [12] developed a practical EVC system and applied it into micromachining of hardened steel dies for a front light panel of liquid crystal display (LCD). Moreover, Zhang et al. [13] challenged to apply EVC using polycrystalline diamond (PCD) tools into precision cutting of hardened steel.

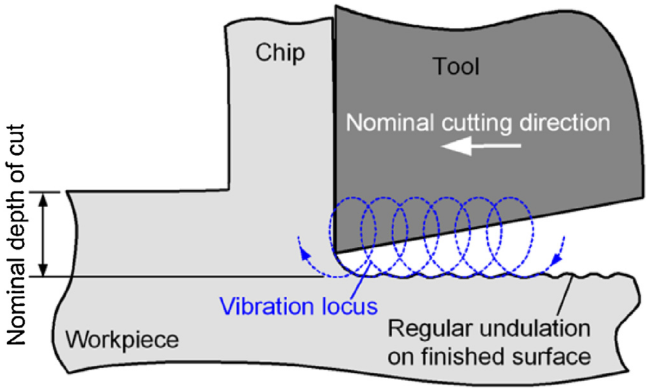

Fig. 1. Elliptical vibration cutting process.

Based on successful cutting performance of EVC, Suzuki et al. [14] explored further possibilities of functional surface machining on difficult-to-cut materials by applying EVC, and proposed a unique micro/nano sculpturing method. In this proposed method, amplitude of the elliptical vibration is actively controlled during machining. Because of this amplitude control, the depth of cut can be changed rapidly without FTS but as being controlled by the conventional FTS technology. Fundamental machining performance was investigated through primitive sculpturing experiments, and simple micro/nano textured patterns were machined successfully on workpieces made of hardened steel and tungsten carbide [14,15]. On the other hand, the proposed amplitude control machining method imposes several restrictions in machinable part geometry, such as height variation range, curvature, and slope angle. These restrictions are directly associated with not only the performance of elliptical vibration equipment but also EVC conditions, whereas theoretical and experimental investigations on restrictions in machinable part geometry have not been conducted enough [14,16]. Hence, it is sometimes difficult to estimate the feasibility of functional surface machining by the proposed method in advance. In addition, the envelope of the cutting edge trajectory is superimposed as a textured surface in this method. As this envelope shape differs from the reference command shape for vibration amplitude control, reference command shape may need to be compensated based on the target shape geometry and EVC conditions for accurate machining.

In order to clarify restrictions in machinable part geometry, theoretical and experimental investigations are conducted in the present work. Subsequently, a compensation method of vibration amplitude command for highly accurate machining is proposed. Through theoretical simulations, restrictions in machinable part geometry are clarified. Based on the clarified restrictions, feasibility of three-dimensional nano structure machining on hardened steel workpiece is explored experimentally, and machining accuracy in nano scale is evaluated. Through a series of experiments and analyses, machining performance of the amplitude control sculpturing method is investigated.

2. Elliptical vibration cutting process and amplitude control sculpturing method

A schematic illustration of the EVC process is shown in Fig. 1. In the EVC process, the tool is fed at a nominal cutting speed