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Micro-dimple pattern process and orthogonal cutting force analysis of elliptical vibration texturing

Rendi Kurniawan [a,*], Gandjar Kiswanto [b], Tae Jo Ko [a,*]

[a] School of Mechanical Engineering, Yeungnam University, 214-1 Dae-dong, Gyeongsan-si, Gyeongsangbuk-do 712-749, South Korea
[b] School of Mechanical Engineering, Universitas Indonesia, Kampus Baru UI, Depok 16424, Indonesia

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ABSTRACT

Elliptical vibration cutting (EVC) has been studied extensively due to its superior performance. Benefits include reduced cutting force, tool wear, burrs, and surface roughness. This paper demonstrates the fabrication of a micro-dimple pattern using elliptical vibration texturing (EVT) based on the EVC method. An analytical model of the texturing process and an orthogonal cutting force analysis are presented. The micro-dimples were successfully established on Al-6061 using different vibration frequencies. The accuracy of the micro-dimples was measured and compared to an analytical model in order to validate the texturing process. The orthogonal cutting force model was used to simplify the cutting mechanism analysis. The effect of transient shear angle is not considered in the texturing process due to the small slope angle of the tool path. The result shows that the analytical model of the cutting force corresponds well with the experimental data.

1. Introduction

Elliptical vibration cutting (EVC) is an alternative cutting method that adds a secondary motion to the tool tip in vibration cutting (VC) to establish an elliptical locus motion of the tool tip [1–3]. The EVC method exhibits superior performance compared to both conventional cutting (CC) and one-dimensional VC (less cutting force [4,5], better surface finish [6–9], burr suppression [10–13], longer tool life [14–17], etc.). Shamoto and Morikawi [2] proposed firstly the EVC method in which they claimed the cutting force and the chip thickness are reduced effectively by using the EVC. Kim et al. [5] and Shamoto et al. [15] reported that by applying EVC during machining, the cutting force reduction was observed. Brehl et al. [1] and Xu et al. [18] presented the comprehensive review of basic kinematic principle between 1D and 2D vibration-assisted machining (VAM) and the characteristics of VAM were explained such as reducing tool forces, extended tool life for diamond tools, reduced surface roughness, and suppression of burr formation. Zhang et al. [17] and Zhou et al. [19] carried out the EVC method with polycrystalline diamond (PCD) tools. Their reports concluded that the steel machining can be applied effectively using inexpensive PCD tools instead of highly expensive single crystal diamond (SCD) tools. Kim and Loh [8] investigated the characteristics of the EVC in micro-V grooving associated with variations of the elliptical amplitudes and the excitation frequency. Then, the micro precision patterns for micro molds were achieved by applying the EVC in which the cutting resistance, tool wear and machining quality were significantly improved [13].

In previous studies, several achievements of creating textured surfaces using conventional machining systems have been carried out. In 1994, Hong et al. [20] proposed a surface-shaping system model to evaluate and simulate the textured surface of machined components by considering the tool geometry and the machine kinematics. Greco et al. [21] introduced a vibromechanical texturing (VMT) method in which only the tip tool vibrates simultaneously normal to the cutting direction. Kurniawan and Ko [22] studied the textured surfaces in turning system using piezoelectric actuated tool holder in which the accuracy of the micro-dimples was measured and evaluated. In turning system, the sinusoidal motion of the tool relative to the workpiece is created by pushing the tool along the depth of cut direction using the piezo electric actuator. Gandhi et al. [23] demonstrated both the plunging-type and sliding-type texturing method for generation of micro-sized dimples and ribs/fins on the surfaces using conventional machining platforms. Matsumura and Takahashi [24] presented the micro-dimple machining based on the milling process on the cylindrical surfaces at high machining rate with 45° cutter axis inclination. Suzuki et al. [7] proposed micro/nano structure sculpturing method in which the amplitude of the elliptical vibration was controlled, and hence the depth of cut could be varied quickly

* Corresponding authors.
E-mail address: tjko@yu.ac.kr (T.J. Ko).

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Nomenclature

a	horizontal vibration amplitude
b	vertical vibration amplitude
f	vibration frequency
t	time
Φ	phase difference
V	cutting velocity
$V_t(t)$	transient velocity vector of the tool tip
$V_x(t)$	tool velocity relative to the workpiece along x-axis
$V_z(t)$	tool velocity relative to the workpiece along z-axis
$\|V_t(t)\|$	magnitude of the tool tip velocity
V_s	shear velocity along shear plane OS
V_c	deformed chip velocity
V_{tt}	tangential component of tool velocity V_t
V_{nt}	normal component of tool velocity V_t
(V/f)	speed ratio
$\theta(t)$	angle of transient velocity vector V_t
$+\ \theta(t)$	slope angle when the value is positive
$-\ \theta(t)$	slope angel when the value is negative
r	chip ratio
ϕ	shear angle
ϕ_a	actual shear angle
ϕ_m	Merchant's shear angle
α	Rake angle
β	friction angle
γ	clearance angle
φ	tool nose angle
da	micro-dimple length along cutting direction
da_c	actual particulate chip length
La	distance of each micro-dimple along cutting direction
db	micro-dimple width along cross-feed direction
Lb	distance between each micro-dimple along the cross-feed direction
H	micro-dimple depth
R	tool nose radius
Δd	distance between the workpiece surface and neutral-axis
t_1	time when the tool tip starts cutting
t_2	time when the tool tip ends cutting
t_3	time when one cycle period beginning to cut
λ	wavelength of elliptical trajectory
N	number of wavelength
N_1	number of wavelengths in cutting path L_1
N_2	number of wavelengths in non-cutting path L_2
K	integer number of wavelengths
n	floating number of wavelengths
z	distance to move the tool from point 2 to 3 and point 4 to 5
ζ	shift distance of each micro-dimple
τ	effective shear stress in the shear plane
ε	effective plastic strain
$\dot{\varepsilon}^*$	normalized effective plastic strain rate
$TOC(t)$	transient thickness of cut
$A_{cut}(t)$	transient area during cutting
$F_R(t)$	transient resultant cutting force
$F_{cp}(t)$	transient principle cutting force
$F_{ct}(t)$	transient thrust cutting force

to obtain the micro/nano structures.

By adopting the EVC method, micro-dimples or textured surfaces could be manufactured with elliptical vibration texturing (EVT). The first EVT method applied the EVC method for texturing in a turning process and was introduced in 2013 by Guo and Ehmann [25,26]. The EVT method is a fast and accurate way to produce the micro-dimple pattern. The micro-dimple pattern shape depends on texturing parameters such as the feed of the tool tip, the vibration frequency of the tool, the amplitude of the tool path, and the tool geometry. Guo et al. [26] studied the surface generation mechanics of the EVT process through modeling and experimentations. The micro-dimple shapes were established on cylindrical surfaces using EVT method in ultrasonic ranges about 28 kHz with different feed rates and spindle speeds. Their micro-dimple shapes might be suitable for increasing water contact angle [27] instead of for friction reduction purposes because the micro-dimple arrangement is too close to each other. Anisotropic wettability of hierarchical structures of micro-channels enhances if the micro-channels are built using the EVT method [27]. The micro-channels could be formed by overlapping the micro-dimples in which the shape depends on critical parameters such as the spindle speeds, feed rates, and vibration frequencies [28]. Based on the previous EVT studies, the majority of micro-dimples array and micro-channels were built on cylindrical surfaces in ultrasonic frequency ranges. However, in this paper, the micro-dimples was built on planar surfaces in low frequency ranges using non-resonance transducer. Parameters such as oscillation frequencies and cutting speed were selected properly to make the micro-dimple density and shape suitable for friction reduction applications. The micro-dimple density was kept less than 20% so that the distance among neighboring micro-dimples is large enough to avoid the interaction among them [29]. In addition, the accuracy and the cutting forces analysis of the EVT have not been carried out yet in the previous reports.

In the field of tribology, a micro-dimple pattern is used on a planar surface to enhance lubricant performance. The micro-dimples act as lubricant reservoirs that improve lubricant retention and to capture wear debris [29]. The performance of micro-dimples to reduce the friction coefficient has been investigated widely [30–35]. A laser surface texturing (LST) is a well-known and common method used to manufacture micro-dimple pattern on a planar surface [36]. The LST method is a fast and flexible process and provides excellent control of the shape and dimensions of micro-dimples. However, if the LST process uses a high-intensity laser beam, melting and rapid solidification of the metal cannot be avoided [33]. In addition, expensive equipment and a clean environment are required in the LST method. These weakness do not occur in the EVT method, which is fast, accurate, and controllable.

In the material removal mechanism, the cutting force is an important parameter, especially for improving the efficiency of the cutting process, as well as for cutting tool and machine design. The cutting force depends on how much material has been cut [37–40]. Shamoto et al. [37] reported calculation method based on time instants at various critical tool locations for determining cutting force values in the EVC process. Kim et al. [41] studied the cutting force of V-grooving by varying the tilt angle of elliptical trajectory in EVC process. Bai et al. [38] and Zhang et al. [40] analyzed the orthogonal cutting forces of the EVC by applying thin shear plane theory. The variation of the thickness of cut (TOC) and transient shear angle of the primary shear plane were considered as the main factors for transient cutting forces. Zhang et al. [39] calculated the cross-sectional area of the cut and the removed chip volumes per vibration cycle by integrating the cross-sectional area of cut to predict quantitatively the cutting force of the EVC for micro-groove turning process. In most of previous studies, analyzing the material removal mechanism could reveal variation of TOC and the variation of shear angle in primary shear zone. In the EVT process, the material load is varied for a transient thickness of