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Effect of process parameters on micro-textured surface generation in feed direction vibration assisted milling

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ABSTRACT

Surface with certain macro/micro/nano structure has been earning more and more attentions owing to its good tribological behavior. However, some complex texture pattern is hard to fabricate, which hinders its wide application. In this study, feed direction ultrasonic vibration assisted milling (FDUAM), was proposed to realize the easy fabrication of micro-textured surface. Based on tool mapping principle, kinematic analysis was carried out aiming to explore the effect of main process parameters on tool trajectory, and also a surface topography simulation model was build. The numerical analysis results were validated by comparing results with experimental data. Three surface texture patterns, which are “micro-rib”, “micro-scale” and “micro-wave”, were realized at low spindle speed, medium spindle speed and high spindle speed, respectively. A preliminary friction test was at last conducted to investigate the tribological behaviors of various micro-textured surfaces. As results, it is found that the final surface topography is greatly influenced by the matching of vibrating parameters and milling parameters, two key parameters, i.e. η and λ, was supposed to be significant to the actual tool path and empty cutting time and finally the surface finishing. Friction test shows that although the fabricated micro-textures lead to the deterioration of surface roughness in most experimental cases, the three fabricated micro-textures studied in this case all make a great contribution to the improvement of surface friction property, particularly in term of load bearing capacity.

1. Introduction

Surface texture has been proved to be of great benefit for some functional parts, friction component is a typical application case. The main benefit of textured surface is to improve the tribological performance and life of friction surface or seal component. To date, numerous experimental findings have been reported and many successful applications can be found in the fields of optics, automotive, aerospace and so forth [1–5].

With the advancement of manufacturing technology, many approaches have been developed to fabricate surface texture. The available technology includes: reactive ion etching (RIE) technique [6,7], abrasive jet machining (AJM) process [8,9], LIGA technique [10], hot micro-coining [11,12], and laser surface texturing (LST) technique [13–16]. However, the above approaches often have their respective limitations, such as much higher cost, lower efficiency or serious air pollution. Besides, all the present techniques cannot easily realize complex or micro/nano scale texture pattern.

Ultrasonic vibration assisted cutting, exerting extra high frequency vibration on tool or workpiece in cutting process, has been proved to be an effective technology to get obvious process improvement [17–19], increasing machining accuracy, decreasing surface roughness, reducing cutting force, and extending tool life. In recent years, this machining technology is proposed to fabricate micro-textured surface in a fast, convenient and cost efficient way that the above surface texture fabricating technologies cannot reach.

In the field of surface texture, ultrasonic vibration assisted cutting technology is firstly applied in turning. Kim et al. [20] fabricated micro V-groove pattern and micro pyramid pattern on workpieces of pure nickel, nickel alloy and mold steels. Guo et al. [21] fabricated micro-dimple pattern on cylindrical surface using elliptical vibration texturing technic and studied the surface generation mechanics through experimentation and modeling. Using elliptical vibration-assisted turning, Xu et al. [22] utilized rotary ultrasonic texturing technic to generate hybrid micro/ nano-textured surfaces. Zhang et al. [23] fabricated groove and dimple patterns on tungsten carbide surfaces using elliptical vibration cutting. Nestler et al. [24] found that ultrasonic vibration assistance enabled the generation of a micro-structured surface in turning of aluminum matrix composites. Zhang et al. [25] proposed a two-staged vibration-assisted turning process to produce micro-structured surface

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more economically. Guo et al. [26] also generated two-level hierarchical micro-structures on aluminum surface using ultrasonic elliptical vibration cutting and investigated the effect of process parameters on wetting characteristics. Sajjady et al. [27] succeeded in fabricating micro dimples on surface by ultrasonic vibration assisted face-turning. Zhang et al. [28] proposed elliptical vibration cutting (EVC) as a potential functional surface machining technology based on its successful cutting performance. Xu et al. [29] also fabricated different types of tailored surface textures using rotatory ultrasonic texturing with designed diamond tools and studied the wetting properties of textured aluminum surfaces. Liu et al. [30,25] fabricated surfaces covered with evenly distributed micro-dimples by radial ultrasonic vibration-assisted turning.

Milling is another conventional process being superimposed by extra ultrasonic vibration to fabricate surface micro-structure. However, due to the more complex kinematics in milling than that in turning, only a few researchers have addressed micro-textured surface by ultrasonic vibration assisted milling. Ding et al. [31] built an integrated model and simulated the surface generation in two-dimensional vibration-assisted micro-end-milling. Uhlmann et al. [32] found vibration assisted milling to be a feasible way to manufacture surface micro-structure. Tao et al. [33] analyzed the generation of predefined squamous patterned surface obtained by ultrasonic vibration assisted milling. Börneret et al. [34] verified the technology possibility of micro-structured surface with ultrasonic vibration milling by both experiment and simulation. Chen et al. [35] fabricated two types of micro-textured surfaces using two-dimensional vibration assisted milling and found the machined surface had controllable wettability. Börnera et al. [36] superimposed an axial ultrasonic vibration in face milling of cold-working steel and got different surface topographies at various process parameter combinations. Chen et al. [37] investigated the topographies and the wettability of various textured surfaces manufactured by vibration assisted milling technology at a frequency of about 8000 Hz and found machined surface wettability is controllable by process parameters matching.

According to the present reports, vibration assisted milling has complex tool-workpiece motion and has potential to produce more kinds of micro-texture patterns [29,37]. However, with the superimposition of external vibration, no matter what is the vibration application mode, the relative motion between the workpiece and milling cutter becomes more complex, any change of milling or vibration parameter may cause the great change of tool trajectory and multiple cutting edge engagements, the final surface topography changes accordingly. Therefore, due to the complex kinematics in ultrasonic vibration assisted milling, to get the designed or desired micro-structure on surface, previous analysis of cutter-workpiece motion and parameter choosing is very required. Up to now, there is still no clear understanding about the effect of combination of milling parameter and vibrating parameter on surface generation.

On whole, as a low-lost, high-frequency, environmental friendly and controllable approach, vibration assisted milling has potential application in many functional surface manufacturing fields and deserves further and deeper study.

In this study, feed direction vibration assisted milling at an ultrasonic frequency was utilized to realize complex micro-texture on aluminum alloy surface. Kinematic analysis coupled with experimental investigation were conducted to give a deep understanding of the finishing of the surface texture pattern. Also, the tribological behaviors of obtained typical micro-textured surfaces were preliminarily tested.

Total 6 sections are included in this paper. Section 2 gives a two-dimensional kinematic analysis of relative motion of tool and workpiece and discusses the effect of parameter combination on tool trajectory by introducing two parameters of η and λ. Section 3 builds a 3D numerical model of surface topography based on tool mapping theory. Then, Section 4 describes the experiment details of surface machining and tribological test. In Section 5, the numerical results and experimental results are comparatively discussed and analyzed. At last, Section 6 gives a summary of the key conclusions of this study.

2. Kinematic analysis of surface generation

In ideal situation, the topography of machined surface is the reflection of the geometry and trajectory of the cutting edge, as shown in Fig. 1. Although the machined surface morphology is also determined by materials of cutting tool and workpiece, process parameter choosing and so forth, the geometry and trajectory of cutting tool is undoubtedly the most significant factor. In feed direction ultrasonic vibration assisted milling (FDUVM), the cutting tool trajectory changes greatly due to the external vibration excitation, and the machined surface morphology changes accordingly.

Tool tip is the intersection of the main cutting edge and the side cutting edge, in this part, the trajectory of tool tip in FDUVM is analyzed aiming to explore the cutter track variation with comparison of that in conventional milling. The exact trajectory of tool tip is trochoidal curve in conventional milling, as shown in Fig. 2.

According to the coordinate system in Fig. 3, and taking point P as the starting point of calculation, the trajectory of the cutter center can be written as Eq. (1).

$$\begin{cases} x_o = \dfrac{Nnf_z}{60}t + \varepsilon\sin(\theta_k + \psi) \\ y_o = \varepsilon\cos(\theta_k + \psi) \end{cases} \tag{1}$$

where, N is the total number of cutting edge, ($N=2$ for two-flute end mill and $N=4$ for four-flute end mill); n is spindle speed; f_z is feed per tooth; ε is the tool radial runout; ψ is the initial phase of tool radial runout; k is the sequence number of the cutting edge ($k=0$, 1 for two-flute end mill and $k=0$, 1, 2, 3 for four-flute end mill); θ_k is the rotation angle of the kth tool tip.

The trajectory of tool tip in conventional milling can be expressed as follow.

$$\begin{cases} x_k = x_o + r\sin\theta_k \\ y_k = y_o + r\cos\theta_k \end{cases} \tag{2}$$

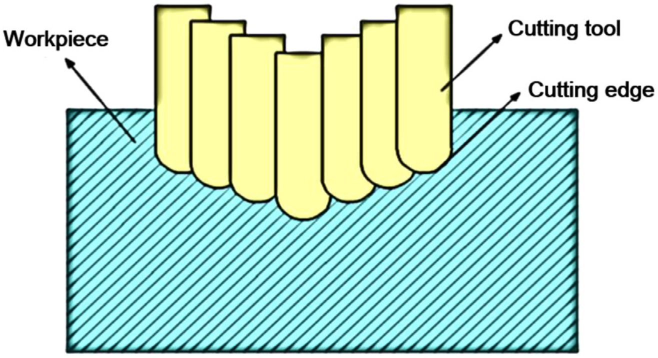

Fig. 1. Schematic view of tool mapping principle.

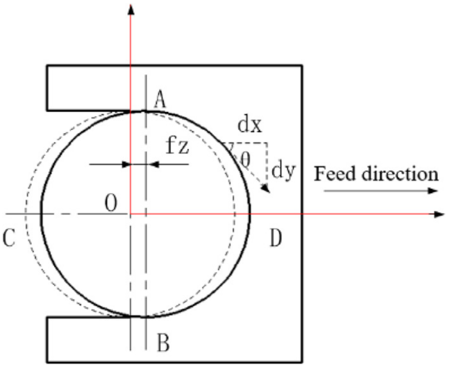

Fig. 2. Diagram of end milling.