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Development of a tertiary motion generator for elliptical vibration texturing

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A B S T R A C T

The elliptical vibration texturing process is an innovative machining method for the fast generation of textured surfaces. It adds a tertiary motion component to the tool tip, which introduces deliberate elliptical vibrations between the cutting tool and the workpiece. The elliptical locus lies in the plane that is defined by the cutting direction and the radial direction in the turning operation. This paper proposes a new design for a resonant mode 2D tertiary motion generator (TMG) that can deliver the required elliptical trajectory at an ultrasonic frequency. The device works in the resonant mode, with tangential and normal vibrations at a nearly identical resonant frequency. Simulation and experiments were carried out to perform a modal analysis of the system. Different design parameters were adjusted to achieve large vibration amplitudes in both tangential and normal directions. The elliptical vibration texturing process was implemented by integrating the newly developed TMG into a turning operation. Preliminary test results of dimple array patterns are presented that validate the performance and principle of the proposed design.

1. Introduction

Surface textures have a decisive impact on the functional performance of products. Proper patterns on structured surfaces could dramatically improve their optical, mechanical, thermal, and biological properties [1]. These structured surfaces usually have periodic patterns with micro/meso-scale features that cannot be fully described by conventional surface topography parameters, such as roughness and waviness. Applications of structured surfaces include friction reduction, heat exchange, optical gratings, superhydrophobic surfaces, etc.

How to accurately and efficiently generate micro-structures on engineered surfaces are a big challenge as well as a timely research topic. At the micro-scale, laser ablation is favorable for its flexibility, but it is usually limited to the prototyping stage because of its high cost and long processing time. It is also limited to non-transparent materials and needs further post-processing. The micro forming method is ideal for mass production; however, it has difficulties with high strength and brittle materials. Besides, how to manufacture the molds with micro features remains a problem.

Micro-machining is well suited at this length scale. It offers significant advantages for its flexibility to process all work materials [2]. Micro-machining with diamond tools, for example, can provide nanometric surface finish without requiring post-processing operations as compared to laser ablation. It increases the geometric accuracy since it eliminates remounting and further operations that degrade accuracy. Currently, however, the only way to machine 3D micro-features is by 5-axis NC controlled machining. Although this method is very accurate, the processing time is not acceptable for mass production.

From the analysis above, it is evident that currently there is limited ability to accurately machine micro-structure features on 3D free-form surfaces, especially at a mass production scale. The limitations in various existing processes for micro-texturing call for a novel machining process, which motivates this paper.

The objective of this paper is to implement an innovative machining method for the fast generation of textured surfaces: *the elliptical vibration texturing process*. The core part of the problem is the development of the tertiary motion generator (TMG) that can generate elliptical vibration trajectories at ultrasonic frequencies. The paper is organized as follows: first, the elliptical vibration texturing process is introduced. Then the development of the TMG is described in detail along with a simulation and experimental analysis. Finally, preliminary experimental results using this newly developed process are presented and followed by conclusions.

2. Elliptical vibration texturing process

The elliptical vibration texturing process originates from the surface-shaping system proposed by Hong and Ehmann [3]. It adds to the cutting tool tip a tertiary motion component, which is a

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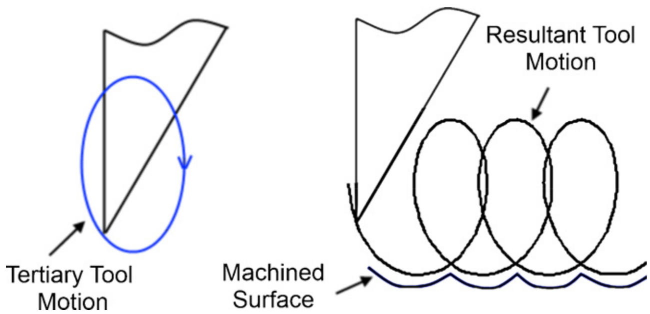

Fig. 1. Principle of the elliptical vibration texturing process.

higher order motion superimposed on the conventional primary and secondary, i.e., cutting and feed motions. It introduces deliberate and controllable vibrations between the cutting tool and the workpiece. The principle of process is shown in Fig. 1. The cutting tool vibrates along a prescribed trajectory with amplitudes of several microns (e.g., an elliptical trajectory as shown in the figure). The resultant tool path imposes textures, i.e., dimples, onto the workpiece surface. The shape and pattern of the texture depend on the shape of the vibration trajectory (the tertiary motion), the cutting speed and feed rate (primary and secondary motions), as well as on tool geometry.

This process is inspired by the idea of the elliptical vibration assisted cutting (EVC) process. Early EVC processes utilized one-dimensional vibrations in the cutting direction, turning the continuous cutting process into an intermittent process. The vibration frequency is usually in the ultrasonic regime, ranging from 20 kHz to 50 kHz. Moriwaki and Shamoto [4] first applied one-dimensional ultrasonic vibration cutting to turning operations. They were able to machine ferrous materials by diamond tools and to achieve optical quality surfaces. Later, they have proposed the idea of EVC, which introduces tool vibrations in both the cutting and chip flow directions in the orthogonal cutting model [5]. This arrangement significantly reduces the instantaneous chip thickness and brings various benefits such as reduced cutting forces, better surface finish, burr suppression, and longer tool life [4–10]. The EVC process also offers advantages in the ductile-regime cutting of brittle materials. It remarkably increases the critical depth of cut, below which the brittle material deforms plastically and forms a crack-free surface [11,12]. Kim and Loh [13] have applied the EVC process to machining micro-channels and pyramidal patterns. Their results have shown significant improvements in surface quality and form accuracy.

The cylindrical turning operation shown in Fig. 2 depicts the difference between the EVC and the elliptical vibration texturing process. Unlike the EVC process, the elliptical vibration texturing process adds vibrations in the cutting and radial directions, while in the EVC process the vibrations are in the cutting and feed directions. The radial vibration dictates the texturing process by varying the cutting depth in the turning operation. The vibration in the cutting direction gives the possibility for generating more complicated texture shapes and patterns. It also brings the benefits of vibration assisted machining into the texturing process, which could lead to the texturing of brittle materials.

3. Development of a resonant mode 2D TMG

The design of the TMG is the key technological problem in the implementation of the elliptical vibration texturing process. There are two possible working principles for the design: the resonant mode and the non-resonant mode. Each working principle has its own advantages and limitations. The resonant TMG works at discrete natural frequencies of the system structure; the

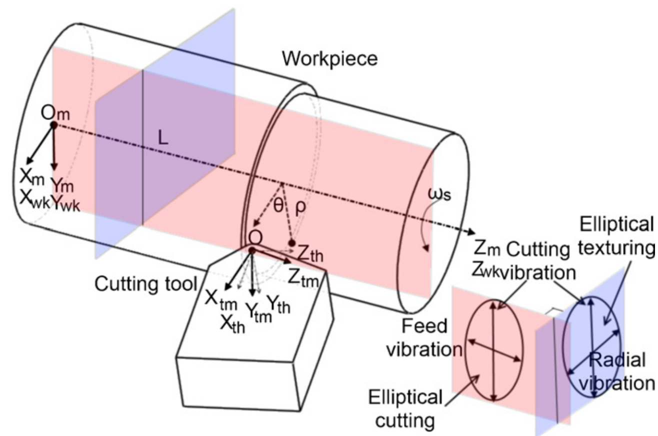

Fig. 2. Illustration of the elliptical vibration texturing process in cylindrical turning operations.

non-resonant TMG works in a continuous frequency range. The resonant TMG is able to achieve a higher operating frequency and is more energy efficient, but a precise control of the trajectory is more difficult owing to the nature of the resonant vibrations and the phase lag between the excitation and mechanical response. The non-resonant TMG is not limited to a fixed operating frequency and offers a more precise control of the motion. It also has the potential to create an arbitrary motion trajectory for complex texture patterns. It is, however, very difficult to achieve a high operating frequency because of various technical problems involved. The scope of this paper focuses on the development of the resonant mode TMG.

3.1. Literature review

The current state-of-the-art design of a resonant mode TMG, which generates an elliptical trajectory, lies in the fields of EVC and ultrasonic motors. A resonant transducer that produces elliptical vibrations at ultrasonic frequencies was developed by Moriwaki and Shamoto [6]. The system is shown in Fig. 3(a). Piezoelectric plates are attached to four sides of a beam. The bending modes in both horizontal and vertical directions are excited by applying alternate sinusoidal voltages to the four piezoelectric plates. Two bending vibrations with proper phase difference cause the diamond

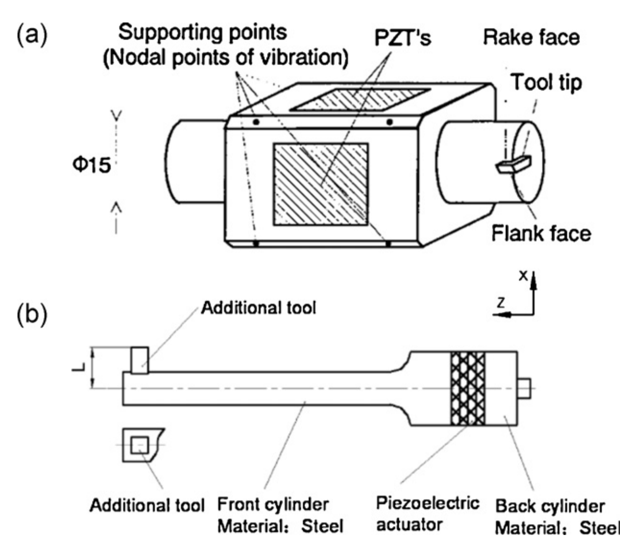

Fig. 3. Traditional resonant transducer designs: (a) Moriwaki and Shamoto's design [6] and (b) Li's design [7].