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Design and application of a flexure-based oscillation mechanism for surface texturing

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ABSTRACT

Micro-textures on tribological interfaces act as micro hydrodynamic bearings that can enhance hydrodynamic lubrication and reduce friction. In this paper, an oscillation mechanism (OM) is employed to generate micro-textures on piston surfaces. The OM is composed of a piezo-actuator and a flexure-based (FB) mechanism in the form of a parallel and symmetric structure with eight circular notch-type hinges. The conceptual design of the FB mechanism is illustrated first. Its stiffness and resonant frequencies are mathematically modeled and verified through FEA. Then, the generation process of micro-textures is analyzed and the relationship between the processing parameters and the parameters of the micro-texture shapes are graphically illustrated. Performance tests of the FB mechanism are also conducted to measure the its output displacement, resonant frequencies and stiffness. Finally, preliminary experimental results confirm that the generated micro-textures on cylindrical surfaces are in accordance with the simulated geometries.

1. Introduction

Of the total energy produced by the piston-cylinder group in a typical automotive engine, about 40% is consumed by engine friction [1]. To reduce friction, the idea of using micro-sized surface textures was studied by researchers, and proven to be effective in improving the tribological performance in sliding applications [2]. Kligerman et al. [3] developed an analytical model to study the potential use of partial laser surface texturing for reducing friction between a piston ring and the cylinder liner. Ronen et al. [4] studied the potential use of micro-surface structures in the form of micro pores by presenting a model to improve the tribological properties of reciprocating automotive components. In their application, the micro-texture features act as micro hydrodynamic bearings to enhance hydrodynamic lubrication [5]. A proper surface texture is a key element in reducing friction in a piston/cylinder system [6]. Well-designed texture features have a beneficial effect on the performance of the lubricant by boosting the hydrodynamic pressure and keeping the interacting surfaces separated [7].

The generation of micro-textures on cylindrical surfaces has also drawn considerable attention because of the potential of substantially improving the friction and lubrication performance between the cylinder and piston rings. Several fabrication techniques, such as chemical etching, abrasive jet machining, reactive ion etching, electrochemical machining and laser surface texturing have been used to achieve micro-textures patterns on cylindrical surfaces [8]. However, these methods are frequently limited in terms of versatility or economics when used in practical surface texture generation. For example, it is difficult to generate micro-textures on non-flat surfaces using chemical etching, abrasive jet machining, and reactive ion etching [9]. Electrochemical machining is slow in productivity, while the laser and optical equipment for laser surface texturing systems needs clean environments [10].

In the present work, a flexure-based oscillation mechanism (FBOM) is integrated into a standard turning process to generate micro-textures on cylindrical surfaces. The fundamentals of this method are based on a mature technology called vibration assisted machining (VAM). During the VAM process, the tool in a conventional machining setting is controlled to vibrate in a manner that results in periodic contact and separation from the workpiece [11], which turns the continuous cutting process into an intermittent process. The VAM process reduces the contact time between the tool and the workpiece, which can be adopted to process difficult-to-machine materials, like stainless steels and titanium alloys [12–14]. In this work, the proposed method to generate micro-textures using FBOM retains the same general principles

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Nomenclature

b	thickness of the hinge
d	the inter-hole space
r	common radius of the notches
l_1	length of the linear spring limb
l_2	distance between the inner side hinge to the center line of the structure
l	distance between the two parallel hinges
K_1,c_1,m	equivalent stiffness and damping coefficients and equivalent mass of the FBM
P_r	excitation force
E,G	elastic modulus and shear elasticity of the flexure material
ρ	density of the flexure material
C	rotational stiffness of the hinge
m_A	mass of the linkage A
m_B	mass of the transitional part B
I_B	moment of the inertia of the transitional part B
f	natural frequency of the FBM
o	oscillation offset
p	distance from the tool's vibration neutral position to the work piece surface
d_c	depth of cut
d_a,d_b	axial width and circumferential length of the texture
L_a,L_b	axial and circumferential spacing of the texture
S	spindle speed
r	radius of the piston
f_r	feed rate
R	the nose radius of the tool
M	vibration amplitude
f_0	vibration frequency
θ	circumferential position of the tool
u_{out}	actual vibration displacement in the depth-of-cut direction
d_c	depth of cut
z_t^i	Z-directional location of the ith position of the cutting edge in o-XYZ
R_0	original radius of the workpiece
r_t^i	distance between the ith position and the tool tip along the rake face
Z_t	Z-directional location of the cutting tool tip
p_1	tool tip
R_e^i	distance from the ith position of the cutting edge to the spindle center o in the XY plane

as the traditional VAM process. It, however, differs in the cutting mechanism. The VAM process utilizes the vibration of the tool to affect the local cutting conditions, e.g., to decrease the effective chip thickness and to reduce the contact time between the tool and the workpiece, while texturing uses the modulation of the cutting depth by the tool vibrations to create surface textures. The spindle speed, depth of cut and feed rate are set in accordance with the vibration magnitude of the cutting tool, in a manner to lead to regular and uniform micro-textures on cylindrical surfaces.

In this paper, an FBOM that works in the non-resonant mode, capable of generating a wide range of required output displacements and, at the same time, retaining high stiffness is proposed. The highly-desirable characteristics of flexure-based (FB) mechanisms, such as their high accuracy and compact architecture, are critical for texture generation. The most promising features of the proposed method are its high efficiency, low cost, and scalability for mass production. The cost of the process is no different than in the conventional machining method, since the process can be easily incorporated into conventional lathes. No expensive or specialized machines are required. The proposed FBOM is composed of a piezo-actuator and a parallel and symmetric FB mechanism with eight circular notch-type hinges [15]. The FB mechanism is conceptually designed. The topological configuration is described first, followed by the stiffness and resonant frequency analysis of the mechanism. The developed mathematical models are subsequently verified through FEA. A stress analysis is also performed using the FEA method. The generation process and the surface parameters of the generated micro-textures' shape are also illustrated. Performance tests of the FB mechanism are then conducted to measure the output displacement, resonant frequency and stiffness. Finally, the developed non-resonant FBOM is integrated into a standard turning machine to implement the vibration assisted texturing process and, the preliminary texturing results are compared with the simulated micro-textures, verifying the feasibility of the proposed FBOM.

2. Conceptual design and analysis of the FB mechanism

In this paper, the FB mechanism is designed as a parallel and symmetric mechanism with eight circular notch-type hinges. The conceptual design of the FB mechanism is illustrated in this section to explore its kinematic and dynamic properties.

2.1. Conceptual design

The structure of the FB mechanism and its motion principle are illustrated in Fig. 1. The FB mechanism is defined in the Cartesian coordinate system $o_c - x_c y_c$. When the piezo-actuator applies a force P_r along the x-axis at the bottom of the flexure mechanism, the eight circular notch-type hinges deform resulting in motions of the platform in the same x-direction. The design objective is to achieve the desired motion range and provide the required stiffness to assure the ability to generate micro-texture features with prescribed geometry.

The schematic of the overall FBOM integrated texturing process is shown in Fig. 2. The FB structure, working in the non-resonant mode, needs to deliver controlled vibratory displacements in the x-direction and simultaneously provide sufficient force and output stiffness. The piezo-actuator is driven by a harmonic or any arbitrary excitation signal. Tool tip displacements with variable amplitude and spacing can be generated by applying suitable excitation signals to the actuator, e.g., sinusoidal.

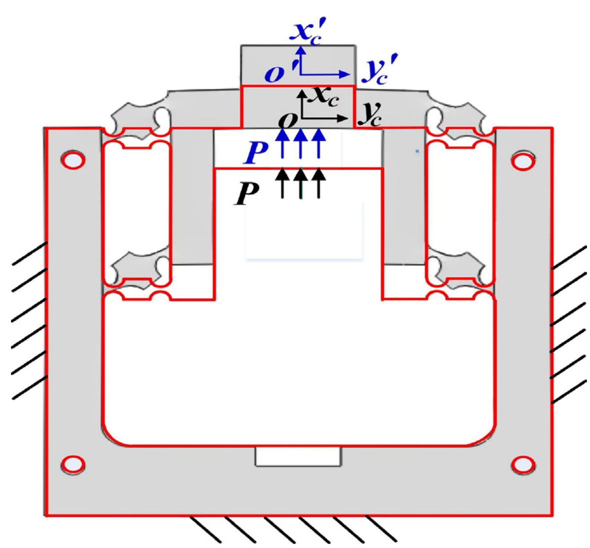

Fig. 1. FB structure and moving principle.