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Design of elliptically-vibrating ultrasonic actuator for nanocoining

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ABSTRACT

Nanocoining is a method of rapidly creating a cylindrical mold surface covered with features smaller than the wavelength of light. This mold can then be used in a roll-to-roll process to make surfaces whose functionality depends on the wavelength of the illumination. The die replaces the typical diamond tool used to produce overlapping grooves for applications such as reflective signs. The die has a face area approximately 20 μm^2 that has been patterned in an FIB. It is mounted on a 2D ultrasonic actuator and follows an elliptical path that matches the surface speed of the moving workpiece during the short contact time and creates approximately 6000 features per impact. The spacing of die indents is controlled by the speed of the diamond turning machine axes such that a small overlap exists from previous indents as the die spirals around and along the mold surface. Because the die is small, the indentations must occur rapidly to make nanocoining a feasible process. This work focuses on the design and control of a nominally 40 kHz, 2D resonant actuator that is suitable for this process. A controller to automatically track resonance is described to maintain the elliptical motion during indentation. Methods of tuning the behavior of the actuator and maintaining a constant indent depth are proposed. Finally, 500 nm pitch feature indents were created on a brass workpiece at 40 kHz and scanning electron microscope (SEM) images of the features are provided.

1. Introduction

Bio-inspired structured surfaces are commonly used in developing coatings that can exhibit a variety of traits, including anti-reflective (AR), superhydrophobic or superhydrophilic qualities. AR surfaces are of particular interest due to their applications in optical lenses, solar cells, and photosensitive detectors [1]. To achieve anti-reflective properties, these surfaces are designed to mimic the nanopillar structures found on the surfaces of moth and butterfly eyes, or cicada and hawkmoth wings. In nature, these AR properties offer survival advantages including camouflage from predators and increased visibility in low light settings [2,3]. Smaller than the wavelength of light, these periodic features introduce a graded index of refection that reduces the amount of reflection compared to an unstructured surface [4]. Moth eye inspired structures have demonstrated an order of magnitude less reflectance over traditional AR thin films in the visible light and near-infrared spectrum [5].

Some of the existing technologies used to generate these nanostructures include interference lithography, etching, and bio-templates [6–8]. Linear gratings can be generated using interference lithography, where two interfering argon ion laser sources are used to create a sinusoidal intensity pattern to which photoresist is exposed [6]. The photoresist surface can then be rotated and exposed to the sources again, producing an array of nanofeatures. Nickel replicates of the photoresist structures were produced and used in an embossing process on acrylic and polycarbonate glass. Another technique for producing nanostructures involves using a bio-template, whereby an anti-reflective biological sample such as the eye of moth or the wing of a cicada is used as a mold to replicate the desired features. In [7], a cicada's wing is replicated by first thermally depositing a thin gold layer on the specimen resulting in a mold of the negative of the features. This gold mold was then deposited with PMMA polymer film to produce a replica of the circada wing features. Non-lithographic etching techniques were used to produce moth eye structures, where monolayer silica colloidal crystals are used as etching masks on the surface of the silicon wafer [8]. Once an array of silica particles is positioned on the wafer, reactive-ion etching (RIE) is used to remove the silicon exposed around the particle mask. After the RIE is complete, the silica particles are removed using a hydrofluoric acid wash, revealing the array of silicon nanopillars resembling moth eye structures. While

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existing techniques are successful in replicating these bio-inspired patterns, they often are long in duration and require several manufacturing steps to complete (some steps in the lithographic process can take up to 11 h [9]).

Nanocoining is a mechanical approach to rapidly create surface structures using a small diamond die (20 μm × 20 μm) containing an array of 6400 nanofeatures machined with a focused ion beam (FIB). This die is pressed into a diamond-turned surface, leaving a field of sub-micrometer features. To create a continuous field of the desired features, the indents are tiled together on the surface of the workpiece. Due to the small size of the die, the indents must quickly cover relatively large areas with nanofeatures in small amounts of time. Previous work at the Precision Engineering Center has shown high-quality nanocoined surfaces at 1 kHz [10] using a non-resonant actuator, however indenting must occur at a much higher frequency for this process to be industrially relevant. To achieve high-frequency indenting, a resonant actuator design must be created with a control system that will maintain resonant actuation with the desired amplitude.

In this paper, the details relevant to the design and optimization of an actuator for nanocoining will be described. The actuator design will be explained by first discussing the performance requirements followed by the design methodology, construction features and tuning techniques. The controllers used to maintain resonance as well as a secondary actuator to track the work surface topology will be described. Finally, results of the system performance will be validated with nanocoining experiments.

2. Process requirements

To create a continuous area of features, the individual die indents must be tiled together. One way this is done is by indenting the surface of a rotating drum on a DTM as shown in Fig. 1(a). The die must be held by an actuator that pushes it into the surface to replicate the die features while moving tangentially at a speed that matches the surface of the drum during contact to avoid smearing of the individual features. The drum surface speed is controlled by the spindle motor rpm and the radius of the drum. In addition to matching the drum speed during impact, the die must land one die width ahead of its position on the last cycle. This defines an "upfeed" distance that sets the relationship between the frequency of the die motion, its size and the surface speed of the drum. The "crossfeed" motion of the linear axis holding the die must advance along the drum at one die-width per revolution.

The registration problem is lessened due to the independent requirements for upfeed and crossfeed of the die. There is no requirement that the dies line up on each rotation of the drum only that the surface is fully covered by features. In fact, small overlap between successive die indents is desirable to avoid regions without features which would produce visible diffraction at a frequency related to size of the die. Once the drum is uniformly covered with the desired structures, it is used as a mold in a roll-to-roll process, for example, to rapidly generate features on a flexible plastic medium (Fig. 1(b)).

3. Actuator design

3.1. Previous designs with similar requirements

The requirements for the die actuator are described above and the larger the die and the higher its operating frequency, the shorter time it takes to cover the mold with features. The development of the actuator is based on research at the PEC and elsewhere to create high-speed motion with a path that will replicate, with high fidelity, the die features onto the mold surface.

3.1.1. Elliptical vibration assisted machining (EVAM)

The actuators used for elliptical vibration-assisted machining are similar to those visualized for nanocoining. An often cited review paper by Dow [23] discussed the process and the actuators concepts developed beginning in 1995.

EVAM is a method of machining that adds a small amplitude, high frequency elliptical tool motion and creates intermittent contact between the tool and workpiece as shown in Fig. 2. The goal was to change the chip/tool motion such that the tool would move faster in the vertical direction than the chip and the friction would lift the chip rather than retard it. With an elliptical path, the tool moves cyclically out of the workpiece along with the chip. Because the relative speed between the chip and tool is small, average frictional effects are reduced, which results in an increased shear angle and reduces the cutting force, reducing temperature and prolonging tool life [21,22].

Early systems at the PEC used frequencies on the order of 1 kHz to study the basic physics of the process. To increase the machining rate and avoid audible high frequency noise, EVAM tools have been designed to operate at ultrasonic frequencies (>20 kHz). An example is shown in Fig. 3 [21] of an elliptically-vibrating resonant actuator that operates at 20 kHz. The actuator body is symmetric

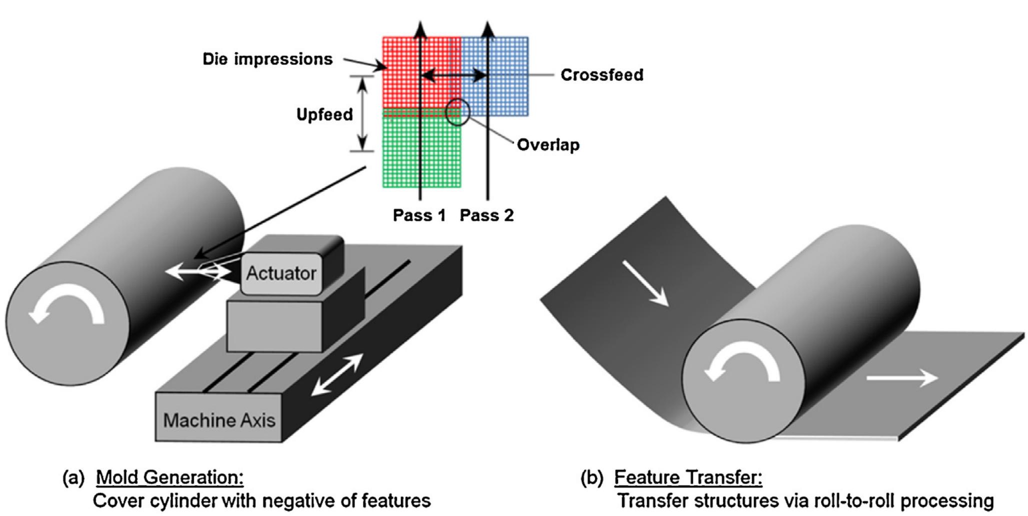

Fig. 1. (a) Nanocoining of subwavelength surface features on a cylindrical mold using the ultrasonically vibrating diamond die and (b) roll-to-roll replication using the indented mold.