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Ultra-precision machining of grayscale pixelated micro images on metal surface

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ABSTRACT

In this paper, a novel machining technique, diamond micro lithography (DML), is developed to provide a possible solution to generate grayscale micro images on metal surfaces. This technique is capable of converting a grayscale image into a pixelated array of customized micro features. The micro feature cell is designed to be a micro inverted pyramid structure as the constituent pixel, which can be engraved by a V-shape sharp diamond tool using a multi-axis ultra-precision machine. Based on an assumption that the perceived luminance by the observer is directly related with the size and geometry of the respective pyramid structure machined, the cell size of each micro feature is designed to have a value linearly related with the grayness value of the corresponding pixel. The distribution of feature-based pixels is determined by superimposed projection algorithm, a customized image processing technique developed in this study to convert the grayscale image to CNC machining codes. A series of machining tests are conducted to evaluate the effect of cell aperture size and cell aspect ratio on the grayness of pixels as well as to prove the assumption made on the relationship between cell geometry and pixel grayness. To explore the performance of DML, the size of machined grayscale image on metal surface is continuously scaled down from 2 mm to 100 μm radius, which is still able to be recognized with the aid of a microscope, demonstrating the capability of DML in transferring pixelated image on metal surface with high fidelity and intelligibility in a wide range of image size. The machined metal workpiece has the potential to be used as mold to replicate the vivid grayscale images onto polymer products for anti-counterfeiting purpose.

1. Introduction

Counterfeit products have been a persistent problem that continuously jeopardizes a healthy commercialization market, and they also discourage innovative effort and cause direct economic losses to the original manufacturer, despite the various protective measures such as security holograms labels. Moreover, compromised quality of the product may eventually result into irreparable harm to the consumers as well as to the healthy economic order. Anti-counterfeiting is considered necessary to protect both the intellectual property and the manufacturing originality. As an effective method in anti-counterfeiting, micro image has already been widely utilized for several decades on money, paper and plastic packages. Although printing technology is able to easily transfer the images on paper or plastic materials, pigment has to be used in the manufacturing process, which is not desirable for quite a variety of products and also has limitation on the smallest image size. To explore more other technologies for image or feature replication without using pigment, researchers have reported several different innovative techniques to machine visually distinguishable features on different materials. For instance, Yang et al. has machined micro patterns to colorize metallic surfaces, using elliptical vibration texturing [1]; Han et al. has fabricated QR code for anti-counterfeiting on drugs through lithography [2]; Wang et al. has generated micro patterns on synthetic diamond crystallites [3]; Wang et al. has machined grayscale micro features on a thin film using direct laser writing [4]. However, until now, there is still a lack of technology to realize direct machining of grayscale micro images on metal workpiece, which can be utilized as a master mold for mass replication of such images on targeted plastic components.

A concave inverted pyramid microstructure is a type of micro feature which is usually used in optics application. The aperture is a square or rhombus, in most cases, with variant aspect ratios to cater for different applications. Nano-pyramid features with sub-micron feature size have been used in the area of light management, such as light harvesting components for high efficiency solar cell reported by Zhao et al. [5], light guidance components in solid state lighting reported by Lee et al. [6], or in surface enhanced Raman spectroscopy to analyze material properties, as reported by Xu et al. [7]. In the authors' previous

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study [8], micro inverted pyramid features have been utilized as gravure cells on gravure roller molds for transferring conductive ink in printing of fine-line electronics.

Due to the significantly large difference on light reflectivity between an inverted pyramid feature and a flat mirror surface, such structure is utilized to represent each pixel, and its feature height is designed to be linearly correlated to the grayness of each pixel, which can be precisely controlled by the machining tool path. By controlling the size and aspect ratio of the machined pyramid structure, the visual luminance perceived by human eyes when looking at the features can be changed. Hence, it could be feasible to control the luminance of each pyramid feature comprising an array of micro pattern like controlling the grayness of each pixel of a digital image. As a whole, a grayscale micro image can be directly machined on a flat surface through accurately controlled luminance distributions to realize the desired contrast and image quality.

In this study, diamond micro lithography (DML) is developed to utilize a sharp-nose diamond tool to machine square inverted pyramid as the comprising pixels, in order to directly generate pigment-free grayscale micro images on metal surfaces. A developed superimposed projection algorithm is developed to realize DML by converting the pixel information of a grayscale digital image into ultra-precision machining codes, which is used to conduct engraving of an array of inverted pyramid micro structures on the workpiece surface. Each pixel element is converted to a micro pyramid feature with its grayness linearly correlated to the feature depth. A tool path program for DML process is generated considering the given image and all the relevant parameters. Micro images with sub–10 μm pixel resolution are successfully fabricated on brass surface in this study. Images with different sizes are successfully machined to demonstrate the capability of DML for micro grayscale image generation on flat surfaces. The machined surface is then evaluated and the given image is found to be well reproduced with satisfied image fidelity and intelligibility. These grayscale images can be observed and recognized by naked eyes, a magnifying glasses or a microscope, depending on the size of the image.

2. Methodology

In this paper, machining of a pixelated grayscale micro image on metal surface is proposed and realized by converting the pixels of a grayscale image to depth-dependent inverted pyramids engraved by a sharp-nose diamond tool.

2.1. Inverted pyramid feature functioning as grayscale pixel

A grayscale digital image is an image in which the value of each pixel is a single number, and varies from black at the weakest intensity to white at the strongest. When a micro image is to be generated on metal surface, a concave feature can be deployed to produce differnet level of luminance to represent the level of darkness of each pixel. Compared to the un-machined zones without any feature, the light rays illuminated on the machined sunken concave features are diverted to other directions instead of being reflected back to the observer. This could result in a relatively lower luminance level perceived at the concave zones.

To achieve such visual effect, an inverted pyramid is considered as a suitable feature due to its symmetric geometrical shape and squarish aperture. The inverted pyramid cells could function as the constituent pixels of the micro image, where each cell surpresses the luminance perceived by the observer at its respective location. The cells will appear to be "dark" to human eyes due to the deviated light reflection compared to the un-machined zones which appear to be "bright", as shown in Fig. 1(a). Idealy, both the engraved cells and flat un-engraved surface should have mirror-like surface finish in order to realize specular relection.

To priliminarily evaluate the variation in darkness level with different cell geometry, simplified simulation is conducted using a commercial CAD design software. As shown in Fig. 1(b) and (c), cell arrays with different aperture size and aspect ratio provide different level of luminance. θ is the included angle of the inverted pyramid feature which is directly related to the aspect ratio, and D is the cell size, i.e. the diagonal length of the pyrmaid feature's aperture.

From Fig. 1(b), it can be observed that, when the same included angle is applied, the luminance level will increase with the decrement of the cell aperture size, due to the larger area of flat un-machined surface. As shown in Fig. 1(c), when the cell aperture size is fixed, the luminance level is affected by the included angle or aspect ratio of the pyramid, and the surface appears to be brighter than that a bigger value of θ, because the extent of deviation for light reflection is relatively less.

2.2. Diamond micro engraving to generate inverted pyramid features

The feasibility for utilizing the inverted pyramid feature to represent the grayscale pixel has been evaluated in the above section. In order to generate such feature on a flat surface, a diamond micro engraving method using ultra-precision machining system is proposed in this study. The idea of diamond micro engraving is to use a sharp-nose diamond tool to machine the workpiece with continuous cutting motion to form an inverted pyramid micro feature. This process is enabled by engaging the C- and X- axes for the controlled angular and linear movement to provide precise positioning, while the depth of cut and the aperture size of the pyramid is controlled by axis of Z (see Fig. 2(b)).

The dimension of such pyramidal features is defined with an aperture of width of w and a height of h. The shape of aperture can be transformed to rhombus by prolonging or shortening the cutting motion along the cutting direction with unvaried depth of cut, to cater for different applications. To ensure the symmetry of the pyramids, both the rake face and its bisecting line (Fig. 2(a)) should be set to be perpendicular to the cutting direction. The rake face is perpendicular to the workpiece surface and parallel to the Z- axis. The geometry of the selected tool is derived from the specific shape and size of the pyramidal features. In this study, the diamond tool used has a sharp nose (< 1 μm nose radius) to machine such sharp edges and corners. To generate the pyramid cells with desired dimensions, the tool included angle, θ, is calculated as follows:

$$\theta = 2\cdot\tan^{-1}\frac{w\cdot\sin{}^{\varphi}/_{2}\cdot\cos\alpha}{h} \tag{1}$$

where α is the effective tool rake angle, and φ is the interior angle of the top rhombus-shaped aperture, as shown in Fig. 2(a). The interior angle is set to be 90°, to make the aperture square. From Fig. 2, it is shown that the rake angle is set to be zero during machining, so the cut-in and cut-out angles, γ_{in} and γ_{out} respectively, should be equal to each other in order to machine a symmetric pyramid where the aperture has equal width, w ($\gamma_{in} = \gamma_{out}$, see Fig. 2):

$$\gamma_{in} = \gamma_{out} = \frac{180^\circ - \theta}{2} \tag{2}$$

Since the feed is kept constant along the surface direction, there is a variation of the tool velocity during the engraving process, and the instantaneous effective rake angle changes consequently. Fig. 2(c) shows a section view of the diamond micro engraving process. A positive rake angle is observed during the cut-in, and soon turned to negative when cut-out. Such variation of effective rake angle will lead to more shearing of material at the cut-in session, and more ploughing of material at the cut-out session, which may result into incomplete material removal or poor surface integrity at the cut-out session in forming a micro feature. Their values can be expressed as follows:

$$\alpha_{in} = \gamma_{in} \tag{3}$$

$$\alpha_{out} = -\gamma_{out} \tag{4}$$

The front clearance angle, δ, plays a crucial role during this process. δ