Optik 124 (2013) 2848–2853

Contents lists available at SciVerse ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Modeling and characterization of generation of 3D micro-structured surfaces with self-cleaning and optical functions

L.B. Kong*, C.F. Cheung, S. To, C.T. Cheng

Partner State Key Laboratory of Ultra-precision Machining Technology, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

ARTICLE INFO

Article history:
Received 11 April 2012
Accepted 17 August 2012

Keywords:
Micro-structured surface
Self-cleaning
Optical performance
Ultra-precision machining
Surface characterization

ABSTRACT

The applications of micro-structured surfaces have been more widespread. They have attracted a lot of attention in the research communities, especially in optics and opto-mechatronics. With the functional requirements, much effort has been made to generate micro-structured surface with self-cleaning properties by methods of using either low-surface-energy materials or modifying the surface structures. However, relative little research work has been found on producing micro-structured surfaces with both optical performance and self-cleaning properties. This paper presents a study for modeling and characterization of the generation of micro-structured surfaces with the properties of self-cleaning and optical performance. A series of simulation and experimental studies have been undertaken to obtain the optimum parameters of the structured surfaces. A typical frustum ridge structured surface has been designed and produced by ultra-precision raster milling, and the geometrical form, static water contact angle, and optical performance are characterized. The preliminary results show that the designed and fabricated micro-structured surfaces with a specified geometrical pattern and scales exhibit both self-cleaning function and the expected optical performance.

1. Introduction

The emerging study of bionics has received more and more research attention during the past few years. Examples can be found in studying the lotus effect of surface with self-cleaning properties which has been widely used in many applications to remove dust or remain clean automatically [1,2]. Examples of these applications can be found in self-cleaning windows, windshields, exterior paints for buildings, navigation of ships, utensils, roof tiles, textiles, and solar panels, etc. Hydrophobicity of the surface which requires strong water repellence depends on several factors, such as surface energy, surface roughness and its cleanliness [3–5]. The research findings suggest two possible approaches to generate such kind of hydrophobic surfaces, which include the use of low surface energy (LSE) material, and the modification of the surface roughness. The former approach is relatively easy to realize but it is limited to a few materials such as Fluorocarbons, Silicones ZnO, TiO_2, etc. [6]. Moreover, they may not satisfy the engineering and functional requirement such as stability and optical performance.

As an alternative approach, the modification of a rough surface with low surface energy is a prospective and flexible method to produce self-cleaning surfaces. Although some research work has been found to produce surface with nano/micro structures to imitate the surface texture of natural animals or plants [7–10], most of them are still focused on the chemical and coating technology. There is a need to investigate advanced self-cleaning surfaces which possess both basic self-cleaning functions and optical functions such as transparency and aberration. The development of ultra-precision machining and precision mould injection technology provides an important means for mass production of microstructures in optics applications [11]. Moreover, different methods for characterization of micro-structured surfaces are also found in the open literatures [12–14]. However, little research has been reported on design and characterization of micro-structured surface with both optical and self-cleaning properties.

As a result, this paper presents a study for the generation and characterization of micro-structured surfaces with the properties of self-cleaning and optical performance. The design criteria for micro-structured surfaces with both self-cleaning and optical functions are firstly presented, and then two typical micro-structures are modeled by mathematical approach. A series of simulation and experimental studies have been undertaken to obtain the optimum parameters of the structured surfaces. Two typical structured surfaces, namely frustum ridge and frustum pillar, have been designed and machined by ultra-precision raster milling. The geometrical form, static water contact angle, and optical performance for the produced plastic parts by mould injection are characterized in the present study.

* Corresponding author. Tel.: +852 2766 6574; fax: +852 2764 7657.
E-mail address: mfboby@polyu.edu.hk (L.B. Kong).

0030-4026/$ – see front matter
http://dx.doi.org/10.1016/j.ijleo.2012.08.061

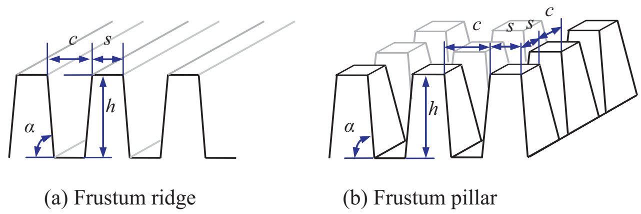

Fig. 1. Typical structured surface design. (a) Frustum ridge and (b) frustum pillar.

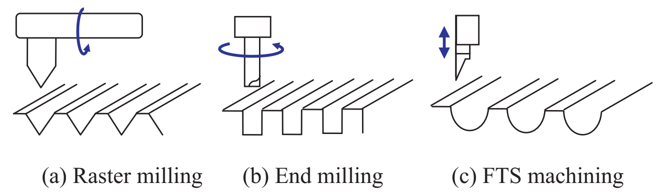

Fig. 3. Selection of ultra-precision machining to produce 3D-microstructured surfaces. (a) Raster milling, (b) end milling and (c) FTS machining.

2. Theoretical background for micro-structures design

2.1. Micro-structured surface design criteria

A three dimensional (3D) microstructure is initially designed from the extraction and simplification of the micro-structured surfaces in nature which have self-cleaning properties such as lotus leaf and some insects' wings, the scale and geometrical features of which are the optimized results by nature in order to achieve the self-cleaning properties. Then the structures are simplified and modeled based on theoretical analysis including the Young's equation [15] and the findings of researchers such as Wenzel and Cassie [16], etc. The geometrical specifications of the structured surface are optimized by the consideration of optical performance such as transparency or reflectance.

Two typical structured surface and pattern are designed, including frustum ridge (FR) and pillar (FP), as shown in Fig. 1(a) and (b) respectively. The two structured surfaces are described by four parameters, height of ridge or pillar (h), top distance between the ridge or pillar (c), top width of the ridge or pillar (s), and inclination angle of ridge or pillar (α).

In the present research, the different dimensions design for the two types of structured surfaces is investigated so as to achieve both self-cleaning and optical functions. The optimization criteria of the designed micro-structured surfaces include: (1) self-cleaning requirement; (2) optical performance requirement; (3) machining feasibility of the designed structures.

(1) The self-cleaning requirement

The self-cleaning requirement includes a large apparent contact angle so that the superhydrophobicity can be obtained. In this aspect, different contacts such as wetted contact and composite contact are studied. Composite contact is generally desired to obtain large contact angle and hence self-cleaning properties. When composite contact is used, Cassie's approach is given by:

$$\cos\theta_r = f_s\cos\theta_e + f_s - 1 = f_s(1+\cos\theta_e) - 1 \quad (1)$$

where θ_r is the apparent contact angles; θ_e is the equilibrium contact angle (ECA) of the liquid drop on a flat surface made of the surface material; f_s is the area fraction of the liquid–solid contact.

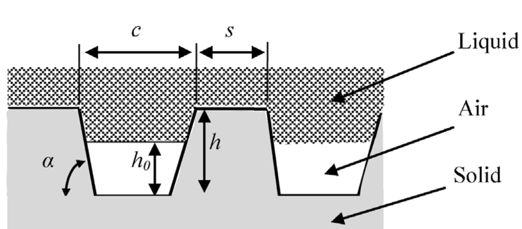

Fig. 2. Composite contact for frustum ridge structures.

For frustum ridge structures, if a composite contact is applied (Cassie's approach) as shown in Fig. 2, the contact ratio is derived as follows:

$$f_s = \frac{s + 2(h - h_0)\cot\alpha}{c+s} \to \min \Rightarrow h_0 \to \max \Rightarrow h \to \max \quad (2)$$

From Eqs. (1) and (2), a smaller f_s is expected to achieve a larger θ_r, and hence a larger depth of the groove h is desired.

(2) Optical performance requirements

For optical transparency, the efficiency of transparency (ET) for frustum ridge structure is derived as follows:

$$ET = 1 - \frac{2h\cot\alpha}{c+s-2h\cot\alpha} \to \max \Rightarrow h \to \min \quad (3)$$

As a result, the structures of frustum ridge design should make a good balance for the depth of the groove so as to achieve the requirements of both self-cleaning and optical performance.

(3) Possible machining ability to produce the designed structures

According to the geometrical design of the micro-structures, a proper machining approach is selected to machine the surface. For example, V-groove such as structures can be produced by ultra-precision raster milling with a V-shaped cutting tool as shown in Fig. 3(a), or the corner groove can be machined by micro end milling (see Fig. 3(b)). Some pillars formed by lens array are possibly achieved by the fast tool servo (FTS) machining as shown in Fig. 3(c).

In order to generate and characterize the designed microstructured surfaces, mathematical modeling for the micro-structures is much needed, which are presented in the following sections.

2.2. Micro-structured surface mathematical modeling

For the two typical structured surfaces as mentioned in Section 2, the mathematics representation is presented as follows:

Frustum ridge is of 2D structures; therefore the profile of the structure can be represented by the features. The profile of the frustum ridge can be described by four parameters: the height of the ridge (h), the top width of the ridge (s), the top width of the groove (c), and the incline angle of the ridge (α), as shown in Fig. 1(a).

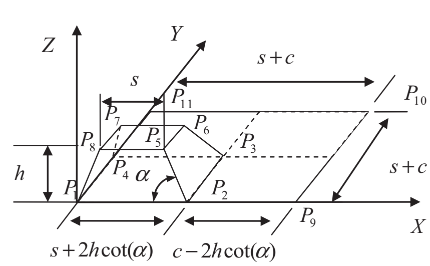

Fig. 4. Vertex of frustum pillar.