A study of the generation and characterization of 3D micro-structured surfaces with self-cleaning and optical functions

L.B. Kong[1, #], C.F. Cheung[1], S. To[1] and C.T. Cheng[1]
1 State Key Lab in Ultra-precision Machining Technology, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
Corresponding Author / E-mail:mfboby@polyu.edu.hk, TEL: +852-2766 6623, FAX: +852-27647657

KEYWORDS : Micro-structured surface, Self-cleaning, Optical performance, Precision surface measurement, Surface characterization; Ultra-precision machining

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 generating and characterizing 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, as well as the mathematical modeling and characterization of these micro-structures are presented. 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 geometry 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 can obtain the self-cleaning function as well as the expected optical performance.

Manuscript received: April 1, 2011 / Accepted: XX XX, 2011

NOMENCLATURE

s= frustum ridge/pillar width
c = groove width
h = height of frustum ridge/pillar
α = inclination of the frustum ridge/pillar
SWCA = Static Water Contact Angle

1. Introduction (Times New Roman 10pt)

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]. 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, TiO2, etc. [6], and sometimes 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. The development of ultra-precision machining and precision mould injection technology provides an important solution 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. A typical frustum ridge structured surface has been designed and machined by ultra-precision raster milling, while the geometrical form, static water contact angle, and optical performance are characterized in the present study.

2. Theoretical Background for Micro-structures Design

2.1 Micro-structured surface design criteria

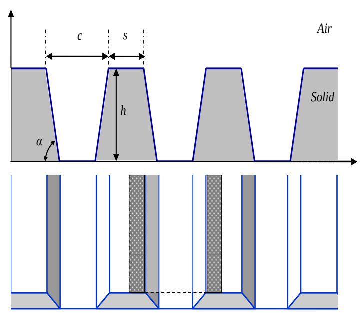
The Three Dimensional (3D) microstructure is initially designed from the extraction and simplification of the micro-structured surfaces in nature which have self-cleaning properties such as lotus leaf and some insects' wings, the scale and geometrical features of which are the optimized results by nature 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. As a result, the optimization of designed micro-structured surfaces during the design includes:

(1) The self-cleaning requirement such as large apparent contact angle so as to obtain the superhydrophobicity;

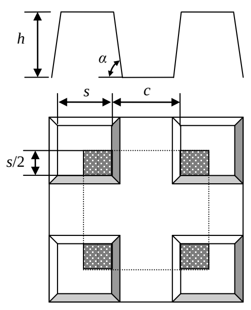
(2) Optical performance requirements such as good transparency or reflection properties;

(3) Possible machining ability to produce the designed structures.

Two typical structured surface and pattern are designed, including frustum ridge (FR) and pillar (FP), as shown in Fig.1 (a) and (b) respectively.



(a) Frustum ridge



(b) Frustum pillar

Fig. 1 Typical structured surface design

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

2.2 Surface mathematical modeling

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

As shown in Fig.1 (a), the profile of the frustum ridge can be expressed as:

$$\begin{cases} z = h, x \in [0, s] \\ z = h - (x - s)\tan(\alpha), x \in [s, s + h\cot(\alpha)] \\ z = 0, x \in [s + h\cot(\alpha), s + c - h\cot(\alpha)] \\ z = x\tan(\alpha) + a - (b + c)\tan(\alpha), x \in [b + c - a\cot(\alpha), s + c] \end{cases} \quad (1)$$

For the frustum pillar, vector representation is employed. Fig.2 illustrates the vertex of one single pillar of frustum pillar structure.

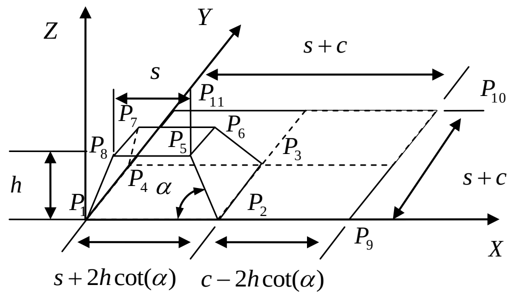


Fig.2 Vertex of frustum pillar

The vertexes of the frustum are expressed as:

$$\begin{cases} P_1 = (0,0,0) \\ P_2 = (s + 2h\cot(\alpha), 0, 0) \\ P_3 = (s + 2h\cot(\alpha), s + 2h\cot(\alpha), 0) \\ P_4 = (0, s + 2h\cot(\alpha), 0) \\ P_5 = (s + h\cot(\alpha), h\cot(\alpha), h) \\ P_6 = (s + h\cot(\alpha), s + h\cot(\alpha), h) \\ P_7 = (h\cot(\alpha), s + h\cot(\alpha), h) \\ P_8 = (h\cot(\alpha), h\cot(\alpha), h) \\ P_9 = (s + c, 0, 0) \\ P_{10} = (s + c, s + c, 0) \\ P_{11} = (0, s + c, 0) \end{cases} \quad (2)$$

3. Characterization and Test of Micro-structured Surfaces

The geometrical feature of micro-structured surfaces can be measured by noncontact optical measuring instruments such as WYKO 3D profiler, Talysurf CCI, Alicona IFM, etc. The surface data from such measuring instruments can be analyzed by the software with the measuring machines, or characterized by the methods developed by the authors [13, 17]. The measurement results from noncontact optical measuring instrument are not only used to analyze the structures feature, but also taken as the reference for the later self-cleaning test. This is undertaken by using water contact equipment such as Drop Shape Analysis System (DSA). Optical performance test of the designed structured surface can be carried out in optical software by rays tracing such as ASAP from Breault Research Organization (BRO), Inc., USA.

Fig. 3 shows a flow chart for the optical performance test of structured surfaces. The structured surface is designed and formed to CAD entity and then exported as standard CAD exchange file (e.g. IGS file). Then the CAD file is imported to optical software, and provided with optical object properties such as material, coatings and so on. After that, the optical system is set up such as light source, detector, etc, and hence the light tracing is carried out. Finally, the optical performance of the designed structured surface is analyzed and evaluated.

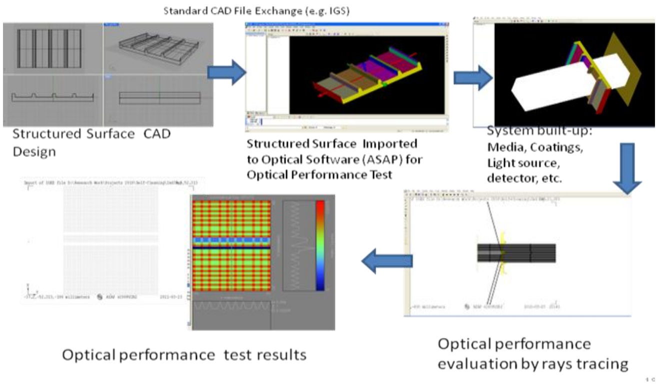


Fig.3 flow chart for optical performance test of structured surface

4. Experimental Studies

4.1 Experiment design

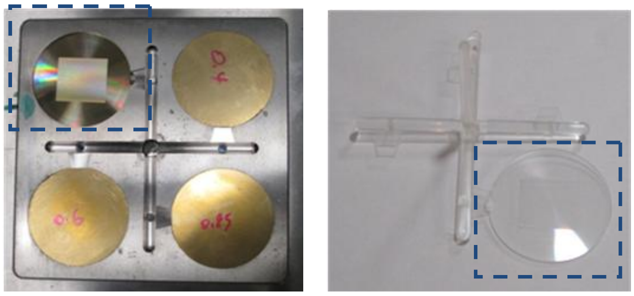
A frustum ridge structured surface is designed and machined by using ultra-precision raster milling. The design specification is shown in Table 1, while the machining parameters are listed in Table 2. A total of 9 samples have been produced with the width of groove variation from 5 µm to 40 µm with the increment of 5 µm. The purpose of the experimental design is to find out the optimum parameters for the frustum ridge, or the transition status from composite water contact (Cassie status) to wetted contact (Wenzel status). The structure form of the frustum ridge is measured by The InfiniteFocus® G4 Microscope (IFM) (Alicona Imaging, Grambach/Graz, Austria). The water contact angle is measured by Drop Shape Analysis System (DSA30) from Taiwan. All contact angle measurements were conducted at 22±1℃ and 50±5% relative humidity. The results of static contact angle were the mean values of measuring ten droplets of 5µl deionized water placed along the groove micro pattern on the sample surface using sessile drop method. Fig. 4 shows the produced mould insert and the mould injection of plastic plat with frustum ridge structures with the design specifications: s=5 µm, c=40 µm, h= 9µm, and α =75°.

Table 1 Design specification of FR structure

Parameters	Values
s (µm)	5
c (µm)	5:5:45
h (µm)	9
α (°)	75
Material	PMMA

Table 2 Cutting conditions in raster milling of FR structures

Parameters		Values
Spindle speed		4,000 rpm
Swing distance		60 mm
Feed rate		100 mm/min
Step distance		0.1 mm
Cutting strategy		Vertical cutting
Cutting tool	Type	Tool A, PLF25.5
	Rake angle	25.5 °
	Clearance angle	12.5 °



(a) Mould with insert (b) Injection plastic plat

Fig.4 Mould injection of plastic plat with Frustum ridge structures

4.2 Results and Discussions

Fig.5 shows the test results for Static Water Contact Angle (SWCA) of the produced plastic plate by the Drop Shape Analysis System. As shown in Fig.5, sample 8 with groove width of 40 µm has the largest SWCA, while sample 9 with groove width of 45 µm has the smallest SWCA. This indicates that water contact transits from composite contact to wetted contact. As a result, the parameters set for this sample is taken as optimum parameter to obtain a large water contact angle. Fig.6 shows the results of the form measurement of the frustum ridge structure with largest SWCA from Alicona IFM G4.

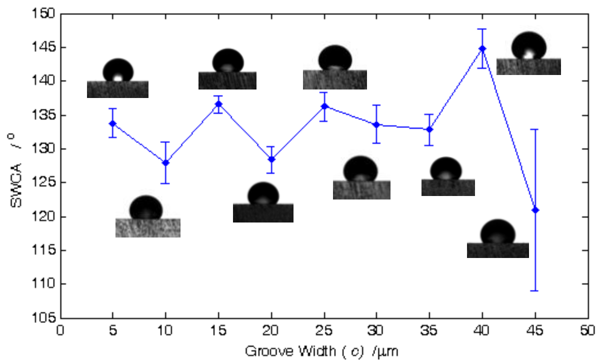
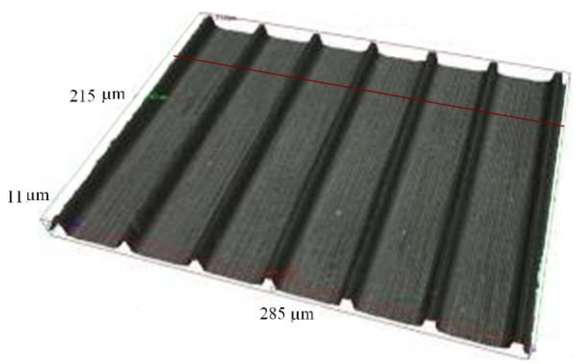
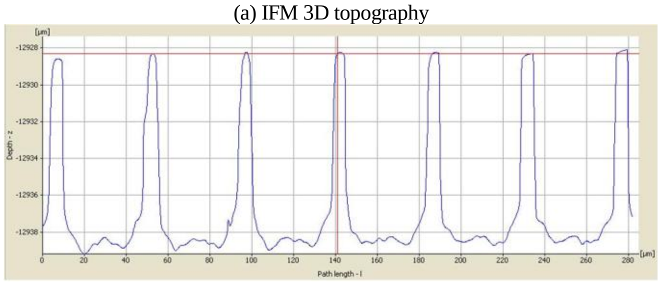


Fig.5 SWCA variations with different groove width(c)



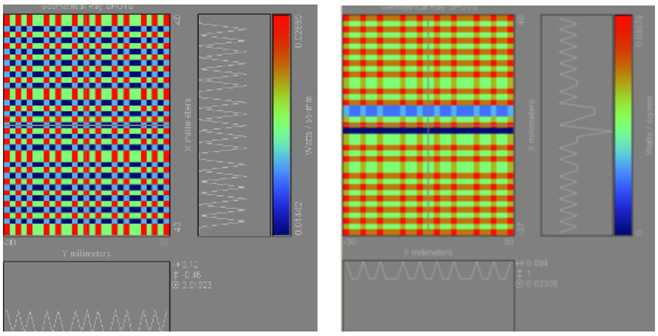
(a) IFM 3D topography



(b) Profile measurement

Fig.6 Measured results of frustum ridge structures

Fig.7 shows a comparison of optical test of the plastic plat with and without FR structures by using the optical software ASAP. The light source is a rectangle grid source. Fig.7 (a) shows the imaging results for the plastic plat without structures, while Fig.7 (b) is the imaging results for the plastic plat with FR structures on one side. From the results, it is interesting to note that the light pattern has been retained and the efficiency is about 91.00%, which indicates that the optical performance of such FR structure can achieve a good result. This is further verified by the practical test results as shown in Fig.8. The imaging effects from the plastic plat with and without the FR structures present almost the same results.



(a) Without structure (b) With FR structure

Fig.7 Optical test of plastic plat

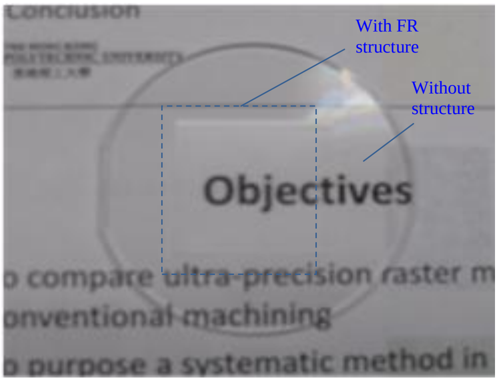


Fig.8 Actual imaging effect (transparency) of the plastic plat with FR structures

5. Future work

Some future work is suggested to be conducted. For example, different material such as Polystyrene and different tool shapes (i.e. Facet tool with a tool width) will be used in ultra-precision raster milling to produce different micro-structured surfaces. Moreover, the aberration and image distortion of the micro patterns on the fabricated surfaces from injection moulding will also be tested by using practical optical testing equipments.

6. Conclusions

This paper presents a theoretical and experimental study for generating and characterizing 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 presented, together with the mathematical modeling of two typical micro-structures. 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 geometry form, static water contact angle, and optical performance are characterized. The preliminary results show that the designed and machined micro-structured surfaces with a specified geometrical pattern and scales can obtain the good self-cleaning function as well as the expected optical performance.

ACKNOWLEDGEMENT

The authors would like to express their sincere thanks to Innovation Technology Commission of the Government of the Hong Kong Special Administrative Region for the financial support under the project (Project code: ITS/390/09)..

REFERENCES

[1] Blossey, R., “Self-cleaning surfaces - virtual realities,” Nature Materials 2, 301-306, 2003.

[2] Bhushan, B., Jung, Y. C. and Nosonovsky, M.., “Lotus Effect: Surfaces with Roughness-Induced Superhydrophobicity, Self-Cleaning, and Low Adhesion, ” Springer Handbook of Nanotechnology, B. Bhushan (Ed.), 3rd edition, Springer. Part F, 1437-1524, 2010.

[3] Adamson, A.V., “Physical Chemistry of Surfaces,” Wiley, New York, 1990.

[4] Israelachvili, J.N., “Intermolecular and Surface Forces,” 2nd edn., Academic, London, 1992.

[5] Nosonovsky, M. and Bhushan, B., “Multiscale Dissipative Mechanisms and Hierarchical Surfaces: Friction, Superhydrophobicity, and Biomimetics, ” Springer, Berlin, Heidelberg, 2008.

[6] Ma, M.L. and Hill, R. M., “Superhydrophobic surfaces,” Current Opinion in Colloid & Interface Science, 11, 193-202, 2006.

[7] Howarter, J.A. and Youngblood, J. P., “Self-Cleaning and Next Generation Anti-Fog Surfaces and Coatings,” Macromol. Rapid Commun. 29, 455–466, 2008.

[8] Song, X.Y., Zhai, J., Wang, Y.L. and Jiang, L., “Fabrication of superhydrophobic surfaces by self-assembly and their water-adhesion properties,” J Phys Chem, B, 109, 4048–52, 2005.

[9] Martines, E., Seunarine, K., Morgan, H., Gadegaard, N., Wilkinson, C.D.W., Riehle, M.O., “Superhydrophobicity and superhydrophilicity of regular nanopatterns,” Nano Lett., 5, 2097–103, 2005.

[10] Hosono, E., Fujihara, S., Honma, I. and Zhou, H.S, “Superhydrophobic perpendicular nanopin film by the bottom-up process,” J Am Chem Soc, 127, 13458–9, 2005.

[11] Lee, W.B., Cheung, C.F., To, S., Kong, L.B. and Jiang, J.B., “Integrated Manufacturing Technology for Design, Machining and Measurement of Freeform Optic,” Chinese Journal of Mechanical Engineering, 46(11), 137-48, 2010.

[12] Gao, W., Aoki, J. and Kiyono, S., “Measurement of Large Area Three Dimensional Micro-Structured Surfaces Using an Atomic Force Microscope,” Reports of Toyota Physical and Chemical Research Institute, 58, 117-121, 2005.

[13] Kong, L.B., Cheung, C.F., Jiang, X. Q., Lee, W.B., To, S., Blunt, L. and Scott, P., “Characterization of Surface Generation of Optical Microstructures Using a Pattern and Feature Parametric Analysis Method,” Precision Engineering, 34, 755–766, 2010.

[14] Yu, D. P., Zhong, X., Wong, Y. S., Hong, G. S., Lu, W. F. and

Cheng, H. L., "An automatic form error evaluation method for characterizing micro-structured surfaces," Meas. Sci. Technol. 22 015105, 2011.

[15] Young, T., "An Essay on the Cohesion of Fluids," Phil. Trans. R. Soc. Lond. 95: 65–87, 1805.

[16] Marmur, A., "Wetting of Hydrophobic Rough Surfaces: To be heterogeneous or not to be," Langmuir, 19, 8343–8348, 2003.

[17] Cheung, C.F., Hu, K., Jiang, X.Q., and Kong, L.B., "Characterization of Surface Defects of Structured Freeform Surfaces Using a Pattern Recognition and Analysis Method," Measurement, 43, 1240–9, 2010.