Hydrophobicity of Pyramid Structures Fabricated by Micro Milling

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Abstract

Surgical site infection is the most common infection, which occurs after surgery in the part of the body where the surgery took place. Hydrophobic structure is an effective method to improve the anti-infection ability of surgical tools. The hydrophobic surface prepared by the conventional chemical coating method has poor durability. In this study, the micro-milling method was used to process the microstructure efficiently. 6 different sizes of microstructure is designed and manufactured on 7C27Mo2 which is commonly used for surgical tools. The capability of applying micro-milling for these structures is assessed. The optimal microstructure size is obtained. The experimental results show that the smooth surface of 7C27Mo2 is hydrophilic with contact angle of 64.1°. However, after micro-cutting, the hydrophilic surface can be converted into the hydrophobic surface, the contact angle contact angle nearly doubled (from 64.1° to 127.3°). This study lays the foundation for the manufacture of surgical tools with hydrophobicity and antibacterial properties.

Keywords: Hydrophobicity, Micro milling, Contact angle

1. Introduction

The hydrophobicity of functional surface has been investigated with considerable attention in the past few years and remarkable progress has been made [1]. A direct expression of the hydrophobicity of a surface is the contact angle of a water droplet. Hydrophobic surfaces can exhibit a contact angle (CA) higher than 90° for water droplets. In particular, superhydrophobic surfaces are generally defined as surfaces which have water contact angles greater than 150°. These functional surfaces have received continued attention for many practical applications, such as self-cleaning, antifogging and frosting, drag reduction and anti-bacteria [2]. In the medical research area, superhydrophobic surfaces can inhibit adhesion and proliferation of bacteria, mainly because of the low surface energy and minimal contact with the surface for bacterial adhesion [3]. Tang et al. observed the adhesion of staphylococcus aureus on surfaces with different wettabilities and found that the cells on superhydrophobic surface more scattered than those on the hydrophilic surfaces and could be easily removed [4]. Due to the extreme bacterial resistance of hydrophobic surface, there is a wide range potential uses on surgical tools and medical equipment. However, the current state-of-the-art for superhydrophobic surface is hindered in terms of the weak durability and short product's life cycle making it unsuitable for practical applications [5]. Thus, a reliable and efficient technology to manufacture hydrophobic surface is essential.

Wenzel and Cassie–Baxter theories show that a rough surface is essential for enhancing hydrophobicity. There is a variety of methods used for the preparation of superhydrophobic surfaces. Mainly include the following: lithography, templating, plasma treatment, CVD-based surface treatment, laser machining and micromachining [6, 7]. Micromachining would be one of the best solutions to high precision manufacturing of micro-textured surfaces with good hydrophobicity due to its programmable control of tool path during the cutting process. This paper mainly focuses on the wetting characteristics of surgical tool material and to obtain the structures which have best hydrophobicity. As surgical tool can be recycled, the durability of hydrophobic structures cannot be neglected. Thus, a highly controllable micro-milling method was chosen to prepare the hydrophobic micro-structured surfaces.

In the machining experiment, micro pyramid arrays are fabricated by micro-milling method. By studying static contact angle, the relationship between the droplet and the array dimension are investigated. Finally, the structure dimensions with the best hydrophobicity are obtained which can be used to guide the manufacture of micro-textured superhydrophobic surgical tools.

2. Material selection and micro structures design

7C27Mo2 is a martensitic stainless steel alloyed with molybdenum that is characterized by good formability and used for surgical tools and surgical instruments. After hardening, it has very good corrosion resistance, high toughness and excellent fatigue strength [8]. Its chemical composition is shown in Table 1.

Table 1 Chemical composition of 7C27Mo2 (%)

C	Si	Mn	P	S	Cr	Mo
0.38	0.4	0.6	≤0.025	≤0.010	13.5	1.0

Song et al. recently reported a modified contact angle prediction model by considering the influence of sloping walls on the contact line between gas and liquid. The research has indicated that sloping side wall has larger contact angle than a vertical wall [9]. Therefore, in this research, the pyramid array was chosen to prepare the hydrophobic structures. The 3D model of micro pyramid arrays is shown in Fig.1. Six samples with different depth, width and spacing micro pyramid arrays are designed. The parameters of the different pyramid array are summarized in Table 2.

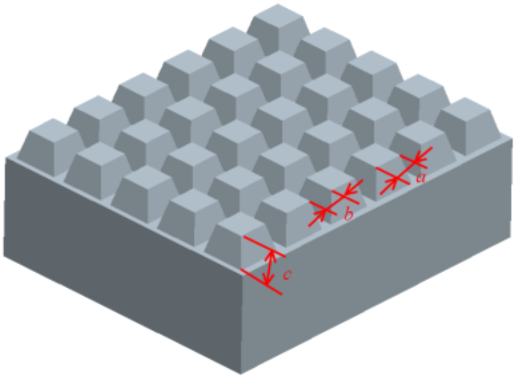


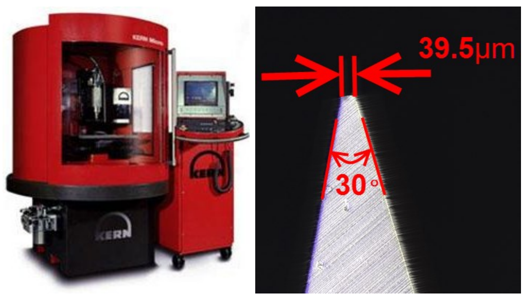
Fig. 1. 3D model of pyramid arrays

Table 2 The design parameters of the different pyramid arrays

Sample No.	*a*(μm)	*b*(μm)	*c*(μm)	Number of Arrays
1	70	70	30	22 Slots
2	60	120	30	16×16
3	100	120	30	15×15
4	10	180	100	20×20
5	20	180	100	18×18
6	50	180	100	16×16

3. Experimental details

A five-axis micro machining center (KERN-2520, see Fig. 2 (a)) is employed to carry out the micro milling experiments. The maximum rotational speed is 50,000 rpm and axis travels are 250 mm for X, 220 mm for Y, 250 mm for Z, respectively. It is equipped with a laser Control NT to measure the micro milling tools.



(a) KERN-2520 (b) Flat V-shaped mill

Fig. 2. Experimental machine and cutting tool

Flat V-shaped tool has many advantages as compared with end milling cutter. The cutting edge of the V-shaped tool has similar shape with pyramid array, thus the microstructures can be machined with a higher efficiency than end milling cutter. Fig. 2 (b) shows a photo of the carbide flat V-shaped engraving mill with a 30° included angle and a 40 μm tool tip width taken by a laser Microscope.

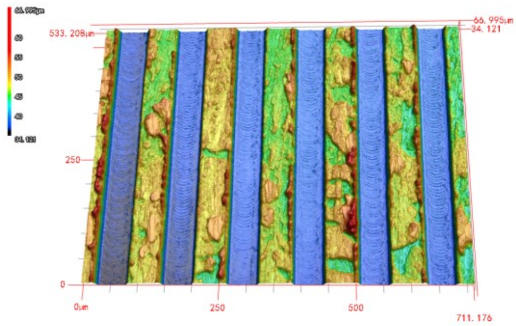
Unidirectional milling was employed to generate V-shaped grooves on the sample surface by horizontal cutting strategy. After finishing the whole micro-slotted surface on the sample, vertical cutting with same step distance was then employed to obtain the final pyramid array. The cutting conditions are shown in Table 3.

Table 3
Cutting conditions

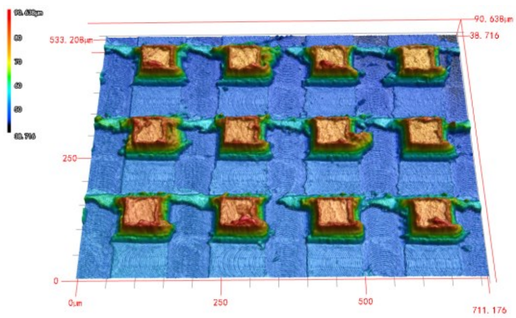
Cutting parameters	Value
Spindle speed	26000r/min
Feed rate	0.6μm/tooth
Axial depth of cut	20μm

4. Micro pyramid arrays topography measurement

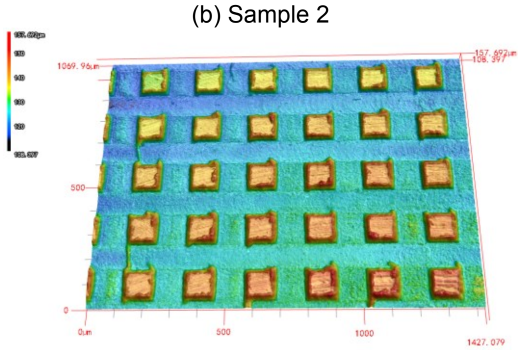
A laser microscope (Keyence VK-X250) was employed to measure surface topographies of micro-directional slots and pyramid arrays which were machined from the experiment as shown in Fig. 3.



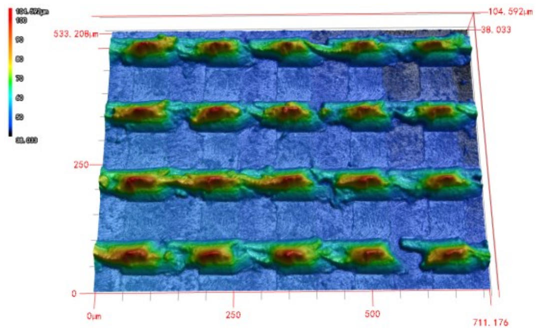
(a) Sample 1



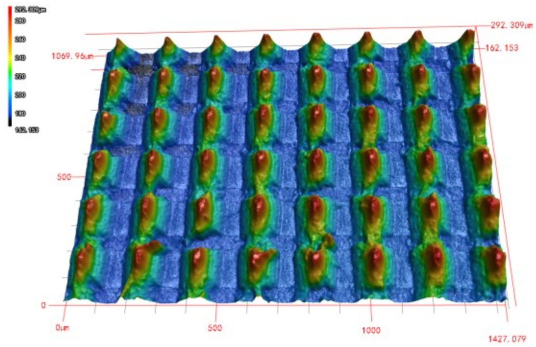
(b) Sample 2



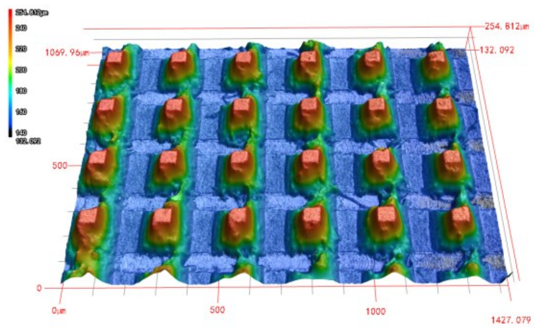
(c) Sample 3



(d) Sample 4



(e) Sample 5



(f) Sample 6

Fig. 3. Surface topographies of different samples

As 7C27Mo2 is a kind of plastic material, surface burrs are clearly observed and mainly located at the edge of pyramids (shown in Fig. 3). Moreover, Samples 4, 5 and 6 have more burrs than samples 1, 2 and 3 due to increase of pyramid height.

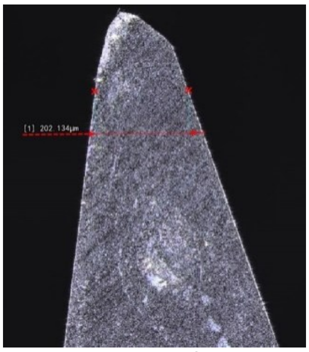


Fig. 4. Flat V-shaped tool (after micro milling)

The measured geometrical parameters of micro-pyramid arrays are listed in Table 4. Pyramids in samples 4 and 5 shown in Fig. 3 have different b and c values in the two orthogonal directions. The deviations between the designed and measured dimensions of pyramid mainly due to the tool wear (see Fig. 4), tool setting error, elastic recovery after the cutting and surface burrs.

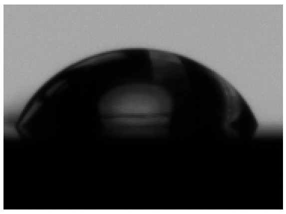
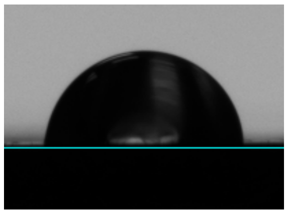
Table 4 Measured geometrical parameters of micro-pyramid arrays

Sample No.	*a*(μm)	*b*(μm)	*c*(μm)
1	55	62	16.3
2	61	111.3	34.9
3	99.9	120.6	26.6
4	3.6	140.1	47.2
5	19.4	176.2	98.7
6	60.3	180.8	96.7

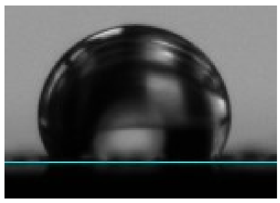
5. Hydrophobicity of micro-patterned surfaces

Static contact angles of water droplets have been measured by the sessile drop method to characterize hydrophobicity of the micro-directional slots and pillar surfaces. A needle extrudes a water droplet on the sample. The water droplet volume is 0.5μL. With an industrial camera and image processing software on a PC, the contact angle can be determined.

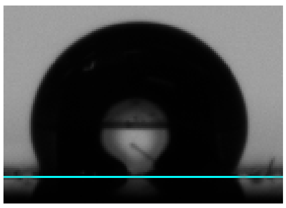
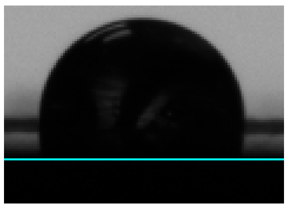
In this research, the static contact angles of the grinding smooth surface (Sa=0.2μm) and micro milling flat surface (Sa=0.5μm) also being investigated. The side views of water droplets on various sample surfaces captured by the camera are shown in Fig. 5.

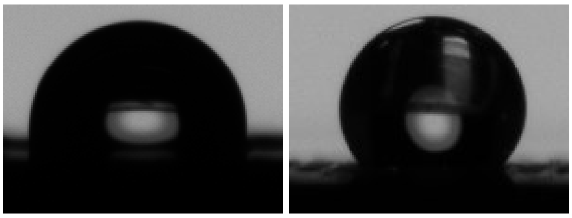
(a) Smooth surface (b) Micro milling surface

(c) Sample 1 (d) Sample 2

(e) Sample 3 (f) Sample 4



(g) Sample 5 (h) Sample 6

Fig. 5. Water droplets morphologies of different samples

The contact angle of different samples is shown in Fig. 6.

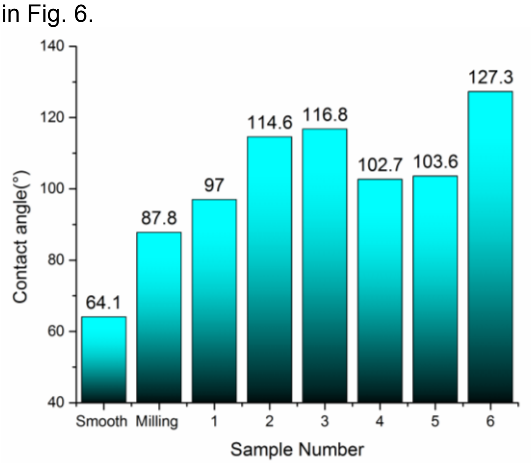


Fig. 6. Contact angle of different samples

From Fig. 6, it can be discovered that water droplets on the smooth surface exhibit a contact angle lower than 90°. Therefore, 7C27Mo2 is a hydrophilic material. Many studies show that hydrophilicity of surface is a major factor for bacterial adhesion and biofilm. Hydrophilic surface or structures attracted most of bacteria such as Staphylococcus aureus. However, micro-milled surface has a larger contact angle (87.8°) than smooth surface due to roughness element make the water droplet change from full wetting to partial wetting.

For sample 1, the contact angle of the slot direction is larger than 90° generally means that it is a hydrophobic structure.

For samples 2 and 3, they have similar V-groove width but different pyramid width. The contact angle test results indicate that the two samples have similar contact angle. Therefore, the width of the pyramid changes from 60μm to 100μm has little effect on the wettability.

The similar trend can be found from samples 5 and 6. The V-groove width of sample 5 and 6 is about 180 μm. But sample 5 has smaller pyramid width than sample 6. Therefore, sample 6 has larger contact angle than sample 5 due to smaller pyramid width cannot support water droplet. All of these results show that micro-cutting is an effective method to improve the surface hydrophobicity. It can make the hydrophilic material 7C27Mo2 hydrophobic. Moreover, the texture has strong durability due to the microstructure is prepared directly on the substrate.

4. Conclusions

In this research, the wetting characteristics of hydrophobic micro-structures machined by a micro-milling process have been investigated. The experimental results show that contact angle of 7C27Mo2 with smooth surface is 64.1°. After micro-cutting process, the hydrophilic surface can be converted into the hydrophobic surface, the contact angle contact angle nearly doubled (from 64.1° to 127.3°).

This research shows that it is feasible to manufacture hydrophobic microstructures with micro milling process. Future work needs to enhance the hydrophobicity, perhaps hybrid process of chemical method or laser machining which enable to get micro-nano composite structures with superhydrophobic characteristic.

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