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Superhydrophobic structures on 316L stainless steel surfaces machined by nanosecond pulsed laser

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ABSTRACT

In this paper nanosecond laser machining process was developed to improve the hydrophobicity of AISI 316L stainless steel surface. A geometrical model of laser machined Gaussian micro hole, together with constrain conditions, was established for the first time to predict surface contact angle and optimize structure geometries for maximizing its hydrophobicity. The effects of processing laser power and pitch of microstructures on the topography of the machined surface were investigated through laser machining experiment. Subsequently, the water droplet contact angle was measured to evaluate the hydrophobicity of different specimens. Results show that under the laser power of 10 W and 14 W, with the increase of the pitch of microstructures, the contact angle increases until it reaches its peak value then drops gradually. Under the large pitch of microstructure, the contact angle will increase with the increase of the processing laser power. Under the same pitch of microstructure, the contact angle will increase with the increase of ten-point height of surface topography, Sz which is a better parameter than Sa (arithmetical mean height) to characterise hydrophobicity of surface with Gaussian holes. This study shows that large Sz is an essential condition to form the stable and robust Cassie–Baxter state, i.e. a condition to achieve superhydrophobicity. The comparison between the predicted and measured contact angles in experiments shows that the proposed model can accurately predict contact angle and optimize the geometries of the microstructure to achieve maximum hydrophobicity.

1. Introduction

Superhydrophobic surfaces have recently received tremendous attention because of special functions such as self-cleaning, corrosion protection, anti-icing, drag reduction and anti-bacteria offered by them [1–6]. Surfaces with water contact angle greater than 150° are generally classified as superhydrophobic surfaces. Many creatures in nature, including the lotus leaf [7], rice leaf [8], butterflying wing [9] and water-strider legs [10] exhibit excellent superhydrophobicity.

Previous researches show that surface coating to reduce surface free energy and fabrication of surface structures are two important methods to achieve superhydrophobic surface [11]. Many approaches for the preparation of superhydrophobic surfaces have been put forward over the last decade, such as electrochemical deposition [12], plasma method [13], chemical vapour deposition [14], wet chemical reaction [15], sol-gel processing [16], lithography [17], electrospinning [18], solution immersion [19], micro milling [20,21], laser machining [22,23] etc. Many surfaces manufactured by chemical methods have good superhydrophobicity but low stability and service life. The major challenges for industrial application of superhydrophobic surface are low production efficiency and high production cost. Instead, laser machining is a reliable manufacturing method due to its high-efficiency and contactless characteristics. Until now, most of laser texturing works use expensive femtosecond or picosecond pulse lasers [24,25]. Many researchers reported that hierarchical structures generated in femtosecond or picosecond pulse laser machining process that consists of micron and nanoscale level pattern is a critical condition for improving surface hydrophobicity [26–28].

Nanosecond laser machining has been proved to be a very promising cost-effective method for surface texturing. Several researchers have paid attention to the study of hydrophobic metal structures machined by using nanosecond laser [23,29–31]. Razi and co-workers carried out research on wettability control on stainless steel by nanosecond laser surface texturing [32–34]. They investigated the surface morphology, surface oxygen content and wettability of specimens machined in air and water [32]. The results showed that the specimen treated in the air has large surface structures than the specimen treated in water [32]. More importantly, they also found a remarkable change from

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hydrophilicity to hydrophobicity after 10 days exposed to ambient air [34]. Duong [23] demonstrated wetting behaviour on nanosecond laser patterned copper and brass surfaces, with the static contact angle of up to 152°. Jagdheesh [29] created near superhydrophobic surface with a maximum contact angle of 148° by using one-step direct laser writing technique. The results show that the micro-holes and the formation of micro-wall play a major role compared with surface chemical change for improving superhydrophobicity. Yang [30] modified the wetting property of Inconel 718 by nanosecond laser machining approach and the maximum contact angle of 156° was obtained. Kwon [31] proposed a sequential fabrication process for a superhydrophobic stainless steel surface, combined with laser machining and electrodeposition, the maximum contact angle obtained was 153°. However, no research has yet been conducted to build a theoretical model used for structure design based on nanosecond laser machining characteristic. The constrained conditions for a stable Cassie-Baxter state superhydrophobic are still not clarified.

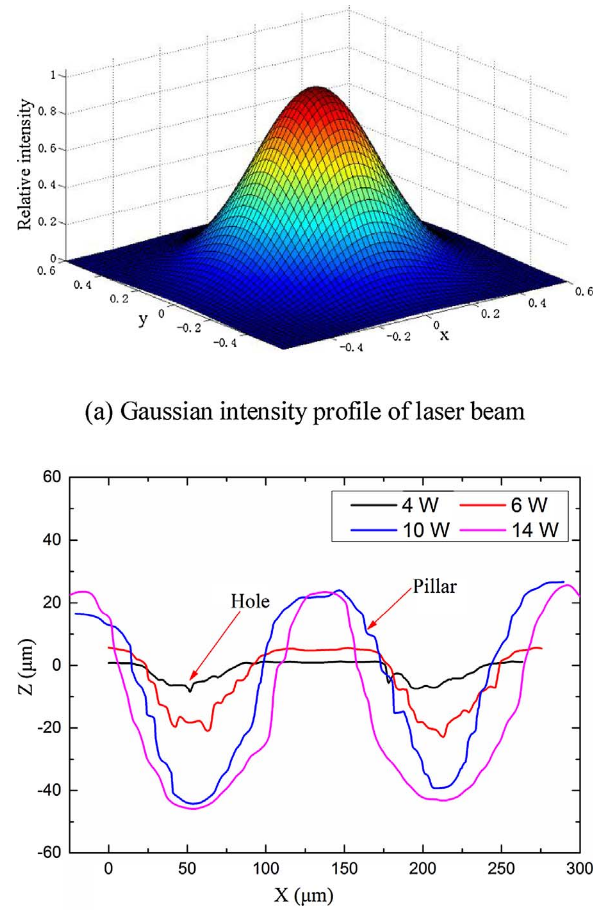
AISI316L stainless steel has been widely used for biomedical implants and surgical instruments, such as hemostat, surgical knives and dental devices. Several studies have been conducted on the superhydrophobicity of 316L stainless steel [11,35]. Chen [11] fabricated the reed leaf-like superhydrophobic structures on stainless steel by nanosecond laser cutting, and the maximum apparent contact angle reached 157°. Trdan [35] reported the wettability modulation from superhydrophilic to superhydrophobic surface state on corrosion behaviour of 316L fabricated by YAG nanosecond direct laser texturing technique. The corrosion resistance test results indicate that the superhydrophobic surface has improved passivation ability and lowest corrosion current density. Thus, superhydrophobicity of 316L is intimately related to its practical application. However, the effects of laser power and structure pitch on surface topography of 316L stainless steel still need further research. In addition, the effects of dimension of structure and surface roughness related evaluation parameter on hydrophobicity of specimen are still unclear.

The above literature shows that nanosecond laser machining is a promising method for manufacturing superhydrophobic structures on 316L stainless steel. However, there are still many challenges need to be further researched. First of all, geometrical model and theoretical analysis of hydrophobicity for laser machined surface need to be established to assist the prediction of contact angle and structure design. Moreover, the mechanism of influence of laser power on 316L stainless steel topography and its superhydrophobicity still requires further research. Besides, the dimension of structure and its effect on hydrophobicity are still unclear.

In this research, we present a high-efficiency and easily-controlled method for manufacturing superhydrophobic surfaces using a nanosecond laser. This work is an attempt to investigate the effects of micro hole structures on hydrophobicity of 316L stainless steel obtained by nanosecond laser under different laser powers. Firstly, the geometrical model based on laser machining Gaussian holes will be built. Moreover, theoretical analysis of the constraints for a superhydrophobic surface will be carried out to explain what kinds of dimension can promote larger contact angle and make the droplet have a stable Cassie-Baxter state on the specimen surface. Then, the micro holes with various pitches will be fabricated on the specimens under various laser powers. The influence of laser power and various pitches on the machined surface roughness will be discussed after surface measurement by SEM and optical microscope. Finally, the measured static contact angle and structure dimensions were compared with predicted values in order to validate and evaluate the prediction model.

2. Prediction model for contact angle based on characteristics of micro Gaussian hole

Our major purpose is to obtain the stainless steel specimen possessing good superhydrophobicity, which means that the droplet should have a stable Cassie-Baxter state on the specimen surface. Thus, in this section, the mechanism of superhydrophobicity will be studied from the theoretical point of view. Moreover, the condition of stable and robust Cassie-Baxter state droplet will also be investigated.



(a) Gaussian intensity profile of laser beam

(b) Surface profile for P110 arrays

Fig. 1. Surface profiles of nanosecond laser beam and machined micro holes.

The nanosecond laser beam has a Gaussian intensity profile as shown in Fig. 1(a), so the profile of laser machined micro hole will be also like a Gaussian curve. In order to investigate the effect of laser power on the surface topography of micro hole, some micro holes with pitch of 110 μm (P110) are machined at different laser powers on stainless steel specimens. Then the surface topography of specimen was measured by an optical microscope (Alicona G4) under 50X Magnification objective. This instrument has a vertical resolution of 20 nm. The surface profiles extracted along the diagonal direction of the machined holes under different laser powers for P110 are shown in Fig. 1(b). The depth and the width of the micro holes are observed to increase in proportion to the laser power. Especially, when the laser power varies from 4 W to 14 W, the average depth of the micro holes gradually increases from 9.2 μm to 68.3 μm. Besides, it also leads to the increase of the height of pillars and decrease of the width of the pillars from 90 μm to 30 μm. The depths of the micro holes are almost the same at 10 W and 14 W, but the pillar width will further decrease as the increase of laser power leads to more materials removed from the specimen surface.

2D profile of micro hole can be described by Gaussian function as shown in Eqs. (1) and (2). For the Gaussian curve, the proportion of area occupied between −3c and +3c is about 99.7%, so the curve between ± 3c was chosen to represent the Gaussian hole machined by pulsed laser.