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Experimental study on the tribological performance of fractal-like textured surface under mixed lubrication conditions

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ABSTRACT

The effect of surface texturing on reducing friction is studied experimentally in this paper. Two types of fractal-like textures and their corresponding regular distribution textures have been fabricated on the surface of AISI1045 steel using a pulse laser, and reciprocating sliding tests were performed on a variable load tribometer (VLT). Friction coefficient of textured surfaces were investigated under various depths and operating conditions. The results show that surface texturing is important for reducing friction. Compared with untextured surface, the textured surface with a depth of 4.7 μm and sliding speed of 153.3 mm/s can reduce friction coefficient up to 48.3%. The fractal-like textured surface has a more effective friction reduction effect than regular distribution textured surface. Comparison of Sierpiński carpet textured surface and circular-based Sierpiński carpet textured surface was studied, and the conclusion was drawn that friction coefficient of the former is smaller than that of the latter under lower sliding speed, however, the conclusion is just the opposite for high sliding speed.

1. Introduction

It is proved that surface texturing is an effective method for improving the tribological performance of the mechanical components [1,2], and various forms and geometric features of texturing for friction reduction and wear resistance are carried out widely [3–6].

The effects of surface texturing on reducing friction and antiwear were depended considerably on the shape, size, depth, density and pattern of dimples [7–10], and optimum texturing parameter for maximum load-carrying capacity and minimum friction coefficient is also related to the test conditions [11,12]. Besides the geometric features, the area density and patterns of textures are also important factors to affect the friction properties of tribo-surfaces. Li [13] found that texture density has a strong effect on the friction and wear behavior, and the surface with texture density of 13% shows the best friction and wear performance. Compared with the untextured surface, it could reduce friction coefficient up to about 50% under the same test conditions. And the result of Li [14] also shows that the texture with the area density of 7.1% has shown the lowest wear rate and longest wear life. Zhang's [15] result indicates that the pattern textured on the ultra-high molecular weight polyethylene surface with an area density ranging from 16% to 30% can effectively reduce the average wear depth, and the maximum reduction rate of the average wear depth is 36% of that of the untextured tribo-pairs. And their result also indicates that the area density of surface texture has great influence on the friction properties, and optimum area density is sensitive to the geometry parameters and operating conditions.

Besides, partial surface texture is an effectual method to optimize the area density and the pattern. Tomanik's [16] study shows that partial LST near top dead center or at middle stroke can produce almost 50% or 90% hydrodynamic support. Kligerman [17] and Zhou's [11] results also show that the minimum friction for optimum partially textured surface is significantly lower than that for the corresponding optimum fully textured surface. Our previous study carried out friction tests on a textured surface with ring-shaped pits under lubrication conditions, and the results show that the staggered array of texture units is effective for antifriction under lubrication conditions [18].

To optimize the surface texturing effect on friction, Segu [19] fabricated multiscale texture dimples (combining circles and ellipses) with some specific formula arrays by laser ablation process, and the result shows that the dimples with a density distribution of about 12% were most effective for friction reduction under the test conditions. And another study of their work [20] that focuses on the friction reduction effect for the multi-shape textured surface on AISI 52100 steel has shown that the multi-shape LST significantly reduces friction under dry and lubrication conditions compared with untextured surface. Moreover, the result coming from Kovalchenko indicates that surface texturing will reduce the friction coefficient and improve load-carry capacity even under boundary and mixed lubrication [21], and Vladescu's [22] results also showed that, as the lubricant film decreases and consequently directs

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Table 1
Chemical composition and mechanical properties of specimens.

Materials		Upper specimen		Lower specimen	
ASTM classification		C26000		1045	
Chemical composition		Pb	≤0.03	C	0.42 ~ 0.50
		P	≤0.01	Si	0.17 ~ 0.37
		Fe	≤0.10	Mn	0.5 ~ 0.8
		Bi	≤0.002	S	≤0.035
		Zn	Bal	P	≤0.035
Mechanical properties	Hardness (HB)	41–76		229	
	Yield strength (σ_s/MPa)			≥355	
	Tensile strength (σ_b/MPa)	340–460		≥600	

Table 2
Shapes and parameters of fractal-like textures.

Parameters	Values		
Average depth of textures Hp/μm	3.0	3.9	4.7
Width of textured region L/mm	12.6		
Shapes of texture units	Square & circle		

the bearing towards the mixed lubrication regime, laser surfaced textures become increasingly beneficial.

In nature, many surfaces of organisms have a fractal feature, such as the lotus leaf. Results of bionic research show that [23–25] lotus leaf-like surface is superhydrophobic. However, the friction reduction effect of surface with fractal textures is rarely reported. The Sierpiński carpet is a famous and commonly used fractal with a long history of application to natural porous media, and is a deterministic and mathematically elegant geometry [26]. The Hausdorff-Becikovich dimension of the Sierpiński carpet is log 8/log 3 ≈ 1.8928 [27,28].

It is not yet clear whether the surface with Sierpiński carpet texture can improve the friction properties than that of normal regular distribution textured surface. Perhaps it is a novel idea to arrange various shapes of texture in a fractal pattern to reduce the friction coefficient and improve wear resistance. This leads to research interest.

In this paper, two types of fractal-like textures and their corresponding regular distribution textures were fabricated on the surface of AISI1045 steel using a pulse laser, and the effect of depth, load and sliding velocity on tribological properties was studied by the experimental method. Comparative study of the fractal textured surface, regular distribution textured surface and untextured surface under the same conditions was carried out.

2. Experimental method

2.1. Specimen and surface texturing

Two kinds of materials with different mechanical properties, C26000 brass and 1045 steel were employed in this study. Brass was chosen as the upper untextured specimen and steel as the lower textured specimen to study the friction reduction effect of the surface texturing. The upper specimen was a cylinder with a diameter of 12 mm, and the lower specimen was processed into cuboid with dimensions of 43 mm × 32 mm × 7 mm (length × width × height). The chemical compositions and mechanical properties of these two materials were shown in Table 1. At first, all lower specimens were cleaned in a pool of ethanol for 15 min in ultrasound, and then were processed into textures by laser ablation. The pulse intensity and moving speed of the laser will be kept constant throughout the whole process in order to ensure that the spot diameter and the ablation depth are constant. Geometrical parameters of textured specimen used in this study were listed in Table 2. After being processed with the textures, all the lower specimens were polished roughly in order to remove the debris around the dimples and then cleaned by ultrasonication in ethanol for 0.5 h, and then dried with flowing air in a laboratory atmosphere (20 °C, RH 35%).

The lower specimens were processed into four types of textured surfaces, including the 3rd generation Sierpiński carpet textured surface (Square Fractal, SF), circular-based Sierpiński carpet textured surface (Circular Fractal, CF) [26] and their corresponding regular distribution textured surfaces (Square Regular, SR and Circular Regular, CR). Figs. 1 and 2 show the schematics of textured surfaces used in this paper. The width of the texture region is expressed by L, and L = 12.6 mm was set for all the specimens. Scales of texture on SR and CR surfaces were decided by the width of the texture region, and can be defined as Eq. (1).

$$S_{ft} = \left(\frac{L}{3}\right)^2 + 8 \times \left(\frac{L}{9}\right)^2 + 64 \times \left(\frac{L}{27}\right)^2 = 81 \times l_{rd}^2 \quad (1)$$

where S_{ft} is the whole area of the textures in textured surface, L is the total width of the texture region, and l_{rd} is the length of square or the diameter of circle for regular distribution texture. Total width of the texture region L is set to 12.6 mm in this paper, therefore the l_{rd} equals to 0.764 mm. The area density of the fractal and regular distribution textures were set to the same, so the influence of area density on friction coefficient should be left out of account. Fig. 3 shows the optical images of four types of surface textures used in this paper.

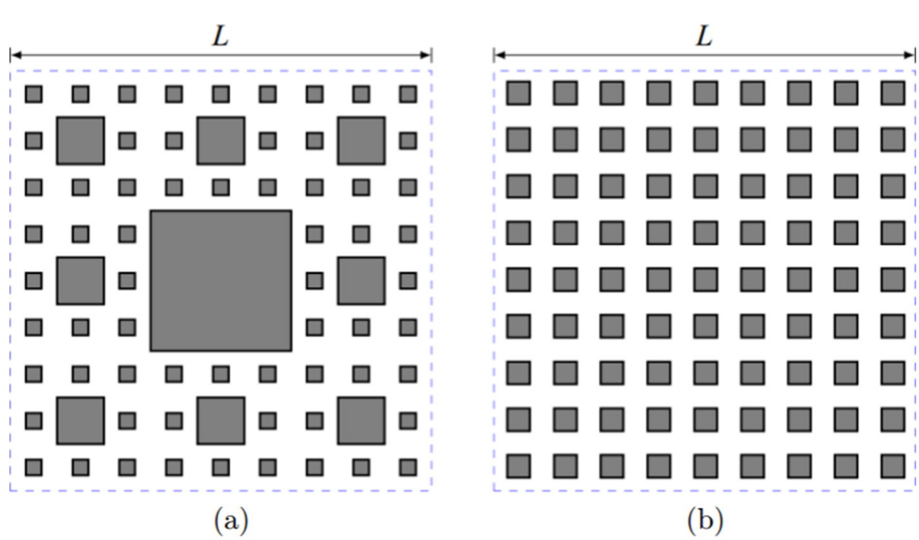

Fig. 1. Schematic of Sierpiński carpet textured surface SF (a) and its corresponding regular distribution textured surface SR (b).