Drop impact on a superhydrophobic surface with single groove

Haiyang Zhan¹, Chengwei Shan², Chenguang Lu¹, Cong Liu¹, Ge Wang¹ and Yahua Liu¹*

¹ Key Laboratory for Precision & Nontraditional Machining Technology of Ministry of Education, Dalian University of Technology, Dalian, Liaoning, 116024, China.
² Dalian University of Technology Library, Dalian University of Technology, Dalian, Liaoning, 116024, China.
*Corresponding author’s e-mail: yahualiu@dlut.edu.cn

Abstract. In this paper, we systematically studied droplets with different velocities impact on grooves with different depths. In the experiment, there are four morphological changes of droplets due to the influence of the impact velocity and the groove depth. Different morphological changes show different spreading characteristics. When the groove depth remains unchanged, the increase of impacting velocity promotes the spreading of droplets in the X (perpendicular to the groove) and Y (parallel to the groove) directions. However, when the impact velocity keeps uniform, the increase of groove depth only promotes the spreading of droplets in the Y direction and has little effect on the maximum spread diameter of the droplet in the X direction. The experimental results also show that the contact time is related to the change of droplet morphology, and their relationship is explained at last.

1. Introduction
Superhydrophobic surfaces have a water contact angle greater than 150° and a rolling angle less than 10° [1-3]. Droplets impacting on a superhydrophobic surface will spread out to the maximum diameter and then retraction to take off the substrate. The time used in this process is called contact time. It is a significant research object for droplets impinging on superhydrophobic surfaces due to the importance of controlling heat and mass transfer and anti-icing. Richard et al. [4] found that the contact time is independent of the impacting velocity but dependent on the droplet diameter, surface tension and the property of the contact surface and so on. The contact time is as small as possible in many practical engineering applications. In order to reduce the contact time, researchers discovered that producing various micro- and macro-structure on the superhydrophobic surface is an effective method [5,6]. Bird et al. [7] reduced the contact time for the first time by changing the hydrodynamic characteristics of droplets and redistributing the morphology and mass of the droplets by adding micro ridges on the superhydrophobic surface. Liu et al. [8] designed superhydrophobic surfaces patterned with lattices of submillimetre-scale posts decorated with nano-textures, which can generate a counter-intuitive bouncing regime: drops spread and then leave the surface in a flattened, pancake shape without retracting. This allows for a fourfold reduction in contact time compared to conventional complete rebound. Shen et al. [9] found that it is impossible to obtain a shorter solid-liquid contact time than spreading time from theory and experiment. Chantelot et al. [10] textured a flat superhydrophobic substrate with point-like superhydrophobic macrotextures, which makes droplets take off as rings and
leads to shorter contact time than on a flat substrate. Zhang et al. [11] investigated that drops impact on oblique superhydrophobic surfaces with two-tier roughness and found a distinct outcome of stretched rebound with respect to traditional sliding rebound, in which the drops rebound more rapidly without tangential retraction, with a 10%~30% reduction of contacting time. Because rectangular grooves can promote asymmetric rebound of droplets, droplets impacting on the grooves are also researched [12,13]. However, the experiments only take the width of the groove into consideration, the depth of the groove is not taken into consideration. In this paper, we systematically studied the effects of the depth of the rectangular groove and the Weber number on the droplet impact morphology, spreading characteristics and contact time.

2. Experimental section

In our study, the superhydrophobic grooves were fabricated on aluminum substrates by combining milling machining and nanoparticle spraying. The width of grooves ($w$) is 2 mm and the depths of grooves ($d$) are 0 mm, 200 $\mu$m, 400 $\mu$m, 600 $\mu$m, and 800 $\mu$m after milling machining. The substrates were then ultrasonically cleaned in ethanol and deionized water for 10 min respectively before drying in air, followed by spraying with commercial never-wet and then drying in the air. The static and dynamic contact angles on the substrates were measured with water drops of 3.36 $\mu$L by using a standard contact angle goniometer. The apparent contact angle and the contact angle hysteresis of superhydrophobic aluminum surfaces are $165.4^\circ\pm1.2^\circ$ and $2.9^\circ\pm1.5^\circ$, respectively. Figure 1a, 1b and 1c show the optical and scanning electron microscopic (SEM) images of the groove with the depth of 400 $\mu$m. The direction perpendicular to the groove is considered to be X, while the direction parallel to the groove is considered to be Y.

A drop is generated from a capillary tube equipped with a syringe pump. The height of the tube is adjusted to vary the impact speed of droplets, as shown in Figure 2. The impact velocity ranges from 0.5 m/s to 1.28 m/s, corresponding to $8.7 \leq We \leq 65$. $We$ is the Weber number which was calculated using the expression

$$We = \frac{\rho D_0 V_o^2}{\sigma}$$

(1)

where $D_0 = 3$ mm is the drop diameter, $\rho$ is the liquid density, $V_o$ is the impact velocity and $\sigma$ is the liquid-gas surface tension. The process of drops impacting on a superhydrophobic surface with single groove was recorded by two high-speed cameras which were both at a frame rate of 10000 fps with a shutter speed of 1/40000 s.
3. Results and discussion

3.1 Morphological changes of drop impact on a superhydrophobic surface with single groove.

Because of different impact velocities and different depths of the groove, four main morphological changes are illustrated in Figure 3. For the purposes of the following description, the four morphological changes are named as: type I, type II, type III and type IV, respectively. Type I is that when droplets impinge on the groove, the asymmetric spread of droplets occurs due to the existence of rectangular groove structure. At 4.4 ms, the droplet spread into a diamond shape, at which time the droplet reached its maximum spreading diameter in the X direction. Then the droplet contracted in the X direction, and a long liquid column was formed at 9.9 ms. Finally, the droplet began to contract in the Y direction; two small droplets connected by a liquid bridge (two lobes) were formed and separated from the surface at 13.6 ms, as shown in Figure 3a (We = 8.7, d = 400 μm). Type II is shown in Figure 3b (We = 32.9, d = 400 μm). Compared with Figure 3a, the groove depth remains unchanged but Weber number increases. Because the kinetic energy of the droplet increases, the spreading area of the droplet on the surface increases. At 2.8 ms, the droplet reached its maximum spreading diameter in the X direction and then the liquid outside the groove began to contract in the Y direction and formed a cross shape around 7.1 ms. Then the droplet began to contract in the X direction, a major droplet and two connected liquid columns (three lobes) were formed and separated from the surface at 9.9 ms. Figure 3c (We = 49.1, d = 400 μm) is type III. Compared with Figure 3b, the droplet detached from the surface after forming the cross shape which can be seen as four connected liquid columns (four lobes). The reason is that when the droplet shrink into a cross shape, the kinetic energy converted from the surface energy is large enough to make the droplet leave the surface. Type IV can be seen in Figure 3d (We = 32.9, d = 800 μm). The droplet became cross-shaped at 6.3 ms. Then the wings broke off at 7.6 ms and the main body separated from the surface at 8.4 ms. Compared with Figure 3c, the spreading area of the droplet decreased with the increase of groove depth d on the surface of the sample and we can observe the breakage of the flanks of the droplet during the shrinkage process.
Figure 3. selected image sequence of drop impacting on the single groove. (a) $We = 8.7$, $d = 400 \mu m$. (b) $We = 32.9$, $d = 400 \mu m$, (c) $We = 49.1$, $d = 400 \mu m$, (d) $We = 49.1$, $d = 800 \mu m$.

The regime map of morphological change of droplets as shown in figure 4. At a lower Weber number, the morphological change of droplet impacting on all the groove is type I. As Weber number increases, the morphological change becomes type II. If the Weber number continues to increase and the groove depth $d$ is larger than $400\mu m$, type III begins to appear. Type IV tends to occur when droplets with big Weber number impinge on grooves of greater depth. With the depth of the groove increases, the Weber number decreases as the type III becomes the type IV.

Figure 4. The regime map of morphological change of droplets.

3.2 Spreading Characteristic.
Different morphologies show different spreading characteristics. Figure 5a, 5b, 5c and 5d show the time evolution of the spreading diameters in the X direction and Y direction ($D_x$ and $D_y$), when droplets produce four morphological changes, respectively. Comparing with figures 5a, 5b and 5c, it is known that when the morphological change is type I, both the $D_x$ and $D_y$ retract; the $D_x$ retracts and $D_y$ doesn’t retract while morphological change is type II; when the morphological change is type III, $D_x$ and $D_y$ do not shrink. That is to say the larger $We$ is, the more obvious the inhibition effect of the droplet shrinkage in the X direction and the Y direction. It is also found that when the groove depth is the same, the spreading diameter of droplets in the X and Y directions increase, with the increase of Weber number.
Compared 5c with 5d, when the Weber number retains unchanged, the larger the groove depth is, the larger the spreading diameter of the droplet in the Y direction is. It is also noted that the spreading speed of the droplets in the Y direction is also greater, as shown in Figure 5e. The reason is that when the depth of the groove increases, the quality of the liquid entering the groove increases. This signifies that the deeper the groove is, the greater the promotion of droplet spreading in the Y direction. The maximum spreading diameters of drops in the X direction on different depth of the groove are measured in the experiment. The maximum diameter \( \frac{D_{\text{xmax}}}{D_0} \) follows the scaling
\[
\frac{D_{\text{xmax}}}{D_0} \sim W e^{0.25}
\]
which is in good agreement with the research of predecessors [14], as shown in figure 5f. That is to say, the groove has little effect on the maximum spreading diameter of drops in the X direction. It is also noted that Dy still increases when Dx reaches its maximum diameter in all experimental results. It is because the rectangular groove changes the momentum distribution of the droplet, making the droplet shows more kinetic in the Y direction.

Figure 5. The variations of the Dx and Dy with time, (a) \( W e=8.7, \ d=400 \ \mu m \), (b) \( W e=32.9, \ d=400 \ \mu m \), (c) \( W e=49.1, \ d=400 \ \mu m \), (d) \( W e=49.8, \ d=800 \ \mu m \). (e) The change of the spreading velocity in the Y direction as time goes. (f) The change of \( \frac{D_{\text{xmax}}/D_0}{We^{0.25}} \) as a function of \( We \) for different groove depths.

3.3 Contact time.
The contact time of droplets impacting on conventional superhydrophobic materials follows the theoretical limit of contact time
\[
\tau \approx 2.6\sqrt{\rho r^3/\sigma}
\]
where \( \rho = 1.0 \times 10^3 \text{kg/m}^3 \) and \( \sigma = 0.072 \text{ N/m} \), so the theoretical contact time is 17.8 ms. Figure 6 plots the variation of the contact time as a function of \( W e \) for different depth of the groove. It can be seen that with the increase of the Weber number, the contact time can be divided into three regions, and the average contact time of the three regions is 12.8 ms, 9.6 ms and 8.7 ms, respectively. It is found that contact time is closely related to the change of droplet morphology. When contact time is 12.8 ms, the change of droplet morphology is type I. When contact time is 9.6 ms, the change of droplet morphology is type II, and when contact time is 8.7ms, the change of droplet morphology is type III or IV. From Section 3.1, we know that droplets consist of two lobes, three lobes and four lobes, respectively, when the shape of droplets changes into type I, type II and type III. Gauthier et al. [15] explored contact time of drops bouncing on a repellent macrotexture and found that the ridge structure causes the asymmetric spread of droplets and leads to the formation of lobes, and ultimately derives
the relationship between the contact time and the number of lobes

\[ t \approx \tau \sqrt{l} \]  

(4)

where the \( l \) is the number of lobes. Therefore, When the droplet generates 2 lobes, 3 lobes, it is approximately 12.2 ms, 10 ms and 8.8 ms, respectively. When the droplet morphology change is type IV, the equivalent mass of the droplet will become 1/4 of its original mass due to the action of the fracture and the groove, so the theoretical contact time also becomes half of the original. It can be seen that the experimental contact time in the experiment is basically consistent with the theoretical contact time. We also notice that when droplets impact on the groove with the depth of 400 μm at \( We = 8.7 \), the contact time is 13.6 ms but the theoretical contact time is 12.2 ms. The main reason is that the theory of Gauthier assumes that the quality of each lobe is the same. However, the quality of each lobe is inconsistent in the real case, so the contact time is different.

Figure 6. Variation of the contact time with \( We \) for different depth of the groove.

4. Conclusion
In this paper, the morphological changes, spreading characteristics and contact time of droplets impacting on rectangular grooves are investigated by the use of high-speed cameras. There are four types of droplet morphological changes due to the influence of the groove depth and Weber number. Type I occurs when Weber number is small. With the increase of Weber number, type II appears. When Weber number continues to increase and groove depth \( d \geq 400 \mu m \), type III appears. Type IV tends to occur when Weber number and groove depth are larger. Different morphological changes show different spreading characteristics. When the groove depth retains unchanged, the increase of Weber number promotes the spread of droplets in the X and Y directions. However, when Weber number retains unchanged, the increase of groove depth only promotes the spread of Y direction and has little effect on the maximum spread diameter of X direction. In addition, it is found that the contact time corresponds to the droplet shape change one by one. When the bounce type is type I, type II, type III or type IV, the contact time is about 12.8 ms, 9.6 ms and 8.7 ms, respectively. It basically coincides with Gauthier’s research.

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