Motion of a Droplet on an Anisotropic Micro-grooved Surface

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Abstract

We experimentally characterise the sliding angle of water droplets (volume 3.1 µL - 22.2 µL) migrating on inclined micro-grooved surfaces along the longitudinal and transverse directions of the grooves. The rectangular micro-grooves are manufactured on silicon wafers using standard photolithography techniques. The droplet motion is recorded using a high-speed camera. The angle of inclination of the surface is systematically varied by virtue of a rotating stage mechanism and its effect on the sliding angle of the droplet while migrating in the longitudinal and transverse directions is investigated. For droplets migrating downward in the transverse direction, the contact line exhibits a “stick-slip” type motion, i.e. the advancing contact line is attached with the surface, while receding contact line is detached from the surface. However, no significant change in the relative position of the advancing and receding contact lines is observed in case of the longitudinal migration of the droplets. The sliding behaviour of the droplet the longitudinal direction is similar to that observed in case of a smooth surface. The sliding angle in the longitudinal direction of motion is found to be smaller.
as compared to that in the transverse motion of the droplet. In both the longitudinal and transverse migrations, increasing the pitch of the grooves increases the contact angle, which in turn decreases the sliding angle. As the droplet volume is increased, the component of the gravitational force in the direction of the inclination increases, which acts to decrease the sliding angle. A theoretical analysis is also conducted to predict the sliding angle of a droplet on micro-grooved surfaces. The model predictions agree with the trends observed in our experiments, and thus validates the proposed sliding mechanisms in the longitudinal and transverse migrations of the droplet.

Keywords: Sliding, Droplets, Micro-grooved surface, Anisotropic wetting

Introduction

The study of droplet migrations on hydrophobic and super-hydrophobic surfaces have been an important area of research due to their relevance in many applications (such as self-cleaning surfaces) and scientific challenges (see e.g. de Gennes\textsuperscript{1} and Bonn \textit{et al.}\textsuperscript{2} and references therein). The application of a body force, external gradients and variation of surface property can be used as mechanisms for motion of a liquid drop. Controlling these physical parameters can play a key role in many industrial applications involving coating processes and microfluidic devices. It is well-established that micro-textures on a surface can be utilized to make a surface hydrophobic. These textures could be isotropic or anisotropic, as seen in several examples in nature, such as micro-pillars (isotropic) on a lotus leaf and micro-grooves (anisotropic) on a shark skin or a butterfly wing. Understanding anisotropic wetting characteristics could be useful to design direction-dependent fluid transport systems. In the present work, we focus on the migration of a liquid droplet on inclined micro-textured solid surfaces having linear grooves with different spacing between them, known as pitch ($P$).

The hydrophobicity of a surface, which is characterised by the degree of water repellency, is usually measured on the basis of contact angle made by the droplet on a solid surface. However, this approach does not always predict the correct physical behaviour, particularly
for droplets with a continuous three-phase contact line and also have small fractional contact
area when placed on a textured surfaces. In these situations, droplet exhibits larger contact
angle, but at the same time experiences higher opposing force leading to reduction in the
tendency of the droplet motion. \(^3\) A more efficient way to measure hydrophobicity of a surface
is to measure the sliding angle, i.e, the angle at which droplet starts to slide on an inclined
surface. In view of this, in past, several numerical and experimental studies measured the
sliding angle of water droplet on different surfaces, and investigated the mechanism associated
with the motion of droplets on different kind of surfaces. A brief review of previous
investigations on this subject is provided below.

Miwa et al.\(^4\) measured the sliding angle of a droplet on rough superhydrophobic sur-
faces using a high speed imaging system. The roughness of the surfaces were varied by
nano-coating smooth glass surfaces with different concentration of FAS-17 (heptadecaflu-
orodecyltrimethoxysilane). They proposed a relationship between the sliding angle, the
contact angle and the surface structure. Yoshimitsu et al.\(^5\) created hydrophobic pillar and
grooved surfaces by dicing silicon wafer and coating with FAS-17. They found that increas-
ing surface roughness by increasing the pillar height increases the hydrophobicity, which in
turn changes the dynamics from the Wenzel state (liquid enters inside the gaps between
the pillar and thereby wetting the whole surface of the pillars) to the Cassie-Baxter state
(when the droplet sits on the top of the pillar). They also observed that parallel injection
favours the droplet sliding more as compared to the transverse injection. The droplet in
the pillared surface showed an intermediate behaviour. Marmur\(^6\) performed a theoretical
analysis using the Cassie-Baxter and Wenzel states to understand super-hydrophobicity of
a model system (paraboloid geometry) that resembles the behaviour of a lotus leaf. Sun
et al.\(^7\) studied the motion of a water droplet on grooved structures fabricated using silicon
wafer coated with FAS. Using high speed imaging, they investigated the effect of surface
roughness obtained by varying the width and spacing between the grooves on the motion of
a droplet. They observed that in the Cassie-Baxter the droplet moves spontaneously in the
direction of increasing surface roughness (towards smaller grooves) on a horizontal grooved surface. However, in the Wenzel state, the droplet has a tendency to move in the direction of decreasing roughness (towards larger grooves).

The flow field inside a droplet moving on a surface prepared using commercial coatings was studied by Sakai et al.\textsuperscript{8} using particle image velocimetry (PIV). They found that the droplet only slipped at high velocity on the superhydrophobic surface (contact angle of 150°). In contrast, on a normal hydrophobic surface (contact angle of 100°) both slipping and rolling motions of the droplet were observed. In another study, Sakai et al.\textsuperscript{9} experimentally investigated the motion of a droplet on different super-hydrophobic surfaces prepared using patterns of ZnO-nanorods of different diameters, and found that the acceleration of the droplet obtained experimentally agrees well with their model developed using solid-area fraction of water droplet on the surface.

Lv et al.\textsuperscript{10} investigated the onset of droplet sliding on inclined micro-pillared surfaces created using photolithography and etching processes and coated with Octadecyltrichlorosilane (OTS). The square pillar sizes were varied from 10 to 30 \( \mu \text{m} \). They observed that at the onset of the motion, at the rear contact lines, first the droplet detaches from the pillar tops. They also developed a theoretical model based on this mechanism of droplet sliding which determines the sliding angle as a function of the fraction of water-solid interface area, droplet volume, and Young’s contact angle. In a similar work, Hao et al.\textsuperscript{11} also investigated the sliding behavior of droplet on a micro-pillared surface with square pillars of size 4 \( \mu \text{m} \). They varied the spacing between them from 4 \( \mu \text{m} \) to 16 \( \mu \text{m} \). The advancing angle was found to be independent of the pillar spacing, but receding contact angle and sliding angle depend on the pillar spacing. As spacing between the pillars increases sliding angle decreases.

Rahman and Jacobi\textsuperscript{12} investigated the dynamics of water droplets of 15 \( \mu \text{L} \) to 75 \( \mu \text{L} \) on micro-grooved brass surfaces by varying the dimension of the grooves. However, the effect of pitch on the sliding behaviour of the droplet was not explored by these authors. Also the dynamics of small droplets (\(< 15 \mu \text{L}\)) was not considered in their study. Recently Zhang
investigated anisotropic sliding behavior of water and oil droplets on micro-grooved organogel surfaces. They observed that the droplet slides when injected in the direction parallel to the grooves, but gets pinned when injected in the direction perpendicular to the grooves. Abolghasemibizaki et al. investigated the effect of viscosity on droplet wetting behaviour on smooth and grooved surfaces coated with functionalized soot. They focused on the rolling velocity of the droplets at different tilt angles and provided a scaling model to predict the rolling velocity of the droplets. However, the groove parameters were kept constant in their study.

In addition to the above-mentioned experimental investigations, several researchers also investigated droplet migrations on smooth surface and surfaces with wettability gradient by performing numerical simulations and lubrication theories. Krasovitski and Marmur theoretically studied relationship between the contact angles at the upper and lower edges of a sliding droplet with its receding and advancing angles, respectively. The dynamics of a two-dimensional droplet on smooth and chemically heterogeneous surfaces were investigated. For hydrophobic surface, they found that the contact angle is approximately equal to the receding contact angle at the upper edge (back), but the contact angle is lower than the advancing contact angle at the lower edge (front) of the droplet. Karapetsas et al. investigated droplet motion on an inclined substrate with temperature varying in the direction of migration of the droplet. The effects of wettability and Marangoni stresses (generated due to the temperature gradient) were investigated. They observed a “stick-slip” motion of the droplet and found that the droplet spreading rate increases due to temperature gradient. Later, this study was extended to investigate the spreading rate of a “self-rewetting” fluid droplet. The rolling and sliding dynamics of a droplet on an inclined surface was studied by Thampi et al. via two-dimensional numerical simulations using a lattice Boltzmann method. They concluded that as the shape of the droplet approaches a circular shape, droplet exhibits rolling motion. Randive et al. investigated the effect of wettability and inclination angle on the droplet dynamics in an inclined channel using three-dimensional
numerical simulations. They found that the effect of inclination on droplet dynamics is more pronounced on hydrophobic substrates as compared to hydrophilic substrates. Farhat et al.\textsuperscript{20} performed three-dimensional simulations to study the static and dynamic wetting of a liquid droplet on a horizontal micro-grooved surface, and compared the wetting patterns observed in micro-grooved and flat surfaces.

As the brief review shows that although droplet sliding behaviour on different surfaces including micro-grooved surface have been investigated by several researchers, to the best of our knowledge, none of the previous studies investigate the droplet migration along and perpendicular to the grooves with varying width and pitch, systematically. Although, as discussed above, the dynamics of a water droplet on micro-grooved surfaces has been studied by few researchers,\textsuperscript{5,12} the variation of pitch of the micro-grooves and dynamics of small droplets have not been explored. Also the mechanisms of droplet sliding on micro-grooved surfaces and a theoretical modelling to explain the sliding behaviour have not been reported by the previous researchers.

In the present study, we systematically investigate the motion and dynamics of a water droplet sliding on micro-grooved surfaces. The distance between the micro-grooves has been varied while keeping the width of the grooves wall constant, thereby increasing the pitch of the grooved surfaces. We know from the past studies that hydrophobicity of the surface depends on the ratio of the width and pitch of the grooves.\textsuperscript{21} The different dynamics observed when the droplet slides on a surface tilted along (longitudinal motion) and perpendicular (transverse motion) to the length of the grooves are investigated. The mechanisms of the sliding behaviour, for a droplet exhibiting the longitudinal and transverse motions are found to be different. In order to explain these mechanisms, analytical models based on force balance\textsuperscript{22,23} and energy balance\textsuperscript{10} have been developed for grooved surfaces, and the theoretical predictions are compared against the experimental results for both the longitudinal and transverse migrations. The droplet size has been varied from 3.1 $\mu$L to 22.2 $\mu$L to study the effect of gravity on the sliding angle of the droplet.
The rest of the paper is organized as follows. The experimental method, which includes surface preparation and the present experimental set-up, is given in Section 2. The results from the experiments are presented in Section 3. A theoretical model is also formulated and the comparison with the experimental measurements are given in this section. Finally, concluding remarks are given in Section 4.

**Experimental method**

**Surface preparation**

The grooved micro-textured surfaces used in our experiments were prepared using standard photolithography techniques. The procedure consists of three steps, namely, (i) preparation of ultraviolet (UV) photo mask, (ii) cleaning of silicon wafer to remove oxides, organic and ionic deposits and (iii) photolithography. In the first step, desired pattern was written on iron oxide coated glass plate (UV photo mask) using laser writer (Microtech, LW405). Then mask was developed in Microposit MF 319 developer (DOW chem. Ind. Pvt. Ltd.) and etched in iron oxide etchant. After that UV mask was cleaned with acetone and isopropanol, and dried by blowing nitrogen gas. In the second step, the silicon wafer was cleaned using RCA cleaning method to remove oxides, organic and ionic deposits. Then this was used as a base surface to make micro-grooved surface. Finally, in the third step, photolithography was performed using Karl Suss MJB4 Mask Aligner. In this process, the silicon wafer was dehydrated at 120°C for 10 minutes and then cooled to 50°C. Then, the silicon wafer was spin coated with SU8-2025 (Microchem Permanent Epoxy Negative Photoresist) at 500 rpm for 10 seconds and 2300 rpm for 35 seconds. After coating, the wafer was pre-baked at 65°C for 3 minutes and 95°C for 8 minutes, and subsequently, it was cooled to 50°C. After that we placed and aligned the mask over coated silicon wafer in Karl Suss MJB4 Mask Aligner, and exposed it to UV radiation for 16 seconds at the rate of 13 mW/cm². Then, silicon wafer was post-baked at 65°C for 1 minute and 95°C for 7 minutes. Further, the wafer was developed
using SU8 photo developer for 5 to 6 minutes. The wafer was cleaned with isopropanol and dried using nitrogen gas. Next, the wafer was hard baked at 120°C for 10 minutes. A nanolayer of platinum (10 nm) was coated on wafer to characterise the micro grooved surfaces using Scanning Electron Microscope (SEM) imaging technique (JSM-7600F, Jeol Inc).

Fig. 1 shows the SEM images of the micro-grooved surfaces with four different pitches, i.e. \( P = 30, 47, 62, \) and \( 76 \, \mu m \) prepared using the above procedure. The width of the walls in all the grooved surfaces was kept constant at 20 \( \mu m \). In Fig. 1, the transverse and the longitudinal configurations are also defined based on the direction of migration on the grooved surfaces. The same nomenclature is used throughout this study.

![SEM images of micro-grooved surfaces](image)

Figure 1: The SEM images of the micro-grooved surfaces with \( P = 30, 47, 62 \) and \( 76 \, \mu m \). The transverse and longitudinal directions with respect to the droplet motion are also shown.

**Experimental setup**

Fig. 2 (a) presents experimental setup used in the present study. A droplet placed on a surface with the back (\( \theta_b \)) and front angles (\( \theta_f \)) of the droplet is shown in Fig. 2 (b). The experimental setup consists four parts. (i) A high speed camera (Photron Inc., SA1.1) with
Figure 2: (a) The schematic diagram of the experimental setup. (b) A droplet placed on an inclined surface showing the front ($\theta_f$) and back angles ($\theta_b$).
long tube objective (Navitar Inc., 12x), which is used to record the droplet motion on micro-
grooved surfaces. The spatial resolution of the camera or the length of the pixel was 17.2 µm.
(ii) LED lamp with controlled illumination capability for the background light source. (iii)
A rotating stage (fabricated in-house) in order to vary the inclination angle of the surface.
In order to avoid the inertial forces due to the rotation, this is designed in such a way that
it rotates at very slow rate (1 - 2° per second). To place the droplet on the micro-grooved
surface and to ensure the consistency and repeatability of droplet placing process, a syringe
was mounted on a retort stand and each set of experiments were repeated three times. The
height from the tip of syringe needle to surface was kept as minimum as possible (always
< 1 mm) to avoid droplet impact on the surfaces, thereby ensuring a gently deposit of the
droplet. To vary the droplet size, we have used different gauges of commercially available
needles (BD Inc.), namely, 31G, 26G, 24G, 21G and 18G having standard (Birmingham
gauge²⁴) orifice inner-diameter 0.133, 0.260, 0.311, 0.514 and 0.838 mm, respectively. The
droplet volumes generated using these needles are 3.1, 6.4, 8.3, 12.7 and 22.2 µL, respectively.
The corresponding uncertainties in the volume generation are 0.28, 0.3, 0.43, 0.9 and 1.89
µL, or 9.0%, 4.6%, 5.1%, 7.0% and 8.5%. After placing the droplet on a surface, its images
are recorded using the high speed camera. The time interval between each recorded image
has been kept the same (20 ms, i.e 50 frames per second). The images are analyzed using a
commercial image editing software “Jasc Paint Shop Pro 7”. Purified deionized water (purity
of 18:2 MΩ) has been used for the droplets. In order to understand the sliding behaviour
of the droplet, it is placed on a horizontal micro-grooved surface, which is tilted gradually.
The dynamics is studied once the droplet starts to slide at any of its edge (front or back)
at a particular tilt angle for a given set of parameters. The sliding angle is defined as the
minimum tilt angle at which one or both the edges of the droplet start to slide. At the onset
of the sliding motion, the tilting process is stopped and the droplet migration is observed.
Results and Discussion

Characterization of micro-grooved surface

Due to the anisotropic nature of the micro-grooved surfaces, the droplet equilibrates to an ellipsoid shape and sits on micro-grooved surface in the Cassie-Baxter state. This in turn results in different contact angles and wetted diameters along the longitudinal and transverse directions of the micro-grooves. To characterize the hydrophobicity and anisotropic nature of micro-grooved surfaces, the contact angle, the wetted diameter $w_d$, the front and back angles of droplets are measured. The variations of these parameters as the fractional area $A_F$ of the grooves is increased for different droplet volumes ($V$) while migrating in the longitudinal (designated by L) and transverse (designated by T) directions are shown in Figs. 3 and 4, respectively. The functional area, $A_F$ is defined as the ratio of the actual contact area of the droplet with the solid surface to the total projected area of the droplet; in our case $A_F = 20/P$. These results are found to be consistent with those of Malla et al.\textsuperscript{21}

Fig. 3(a) shows the variations of the contact angle for different values of micro-groove fractional area, $A_F$ when the droplet migrates in the longitudinal and transverse directions. Fractional area , $A_F = 1$ represents the solid-plain surface without any grooves. As the fractional area ($A_F$) of micro-grooved surface decreases, the contact angle of droplet increases along both the longitudinal and transverse directions of the micro-grooves for all droplet volumes considered. The fractional area decreases with increase in the value of the pitch of the micro-grooves. Thus the contact angle of the droplet increases with increase in the value of the pitch. Also for all values of $A_F$, the contact angle in the transverse direction is higher as compared to that in the longitudinal direction. This happens due to the fact that droplet wets the surface more in the longitudinal direction as compared to the transverse direction as the surface structure is continuous along the longitudinal direction but it is discontinuous along the transverse direction (anistropic nature of the grooved surfaces). The energy barrier for the wetting in case of the longitudinal direction of motion is less as
Figure 3: The variations of (a) the contact angle ($\theta_s^\circ$) and (b) $w_d/V^{1/3}$ with the fractional area ($A_F$) of the micro-grooved surface for both the longitudinal (L) and transverse (T) migrations of the droplet. The maximum errors in the contact angle and the wetted diameter measurements are ±2° and ±0.1 mm, respectively, which includes the repeatability error and the variation in the front and back angles.
compared to the transverse direction of motion of the droplet. This phenomenon is evident in Fig. 3(b), which shows the variations of the dimensionless wetted diameter of the droplet ($W_d/V^{1/3}$) for different values of the fractional area ($A_F$) of the micro-grooved surfaces. It can be seen in Fig. 3(b) that the dimensionless wetted diameter decreases with decrease in the value of the fractional area ($A_F$) for all the droplet volumes considered and for both the longitudinal and transverse migrations of the droplet.

The variations of the front and back angles versus $A_F$ for the droplets migrating in the longitudinal and transverse directions are plotted in Fig. 4 (a) and (b), respectively, for different droplet volumes. It can be seen in Fig. 4(a) that the front and back angles of the droplet in the longitudinal direction increases with the decrease in the value of the fractional area ($A_F$). In contrast, when the droplet migrates in the transverse direction, the front angle remains almost unchanged, but the back angle increases with the decrease in fractional area ($A_F$). Decrease in $A_F$ results in low wettability and higher contact angle, which in turn increases the front and back angles. It can also be observed that the front angle in transverse direction for each value of $A_F$ is higher as compared to that in the longitudinal direction. However, the back angle remains almost same, which results in a higher contact angle hysteresis in case of droplet migration in the transverse direction. This phenomenon was previously reported by Malla et al.\textsuperscript{21} and the reason behind this phenomenon is discussed in the next section.

**Mechanism of droplet motion**

The droplet placed on a micro-grooved surface exhibits an anisotropic wetting behaviour. Also note that the droplets are placed on the micro-grooved surfaces gently and the pitches are not large enough for the droplets to penetrate between the grooves, so we observe that the droplets remain in the Cassie-Baxter state for all the cases considered in this study. In Fig. 5(a), we present the longitudinal and transverse views of the droplet ($V = 12.7\pm0.9 \, \mu\text{L}$) placed on a horizontal micro-grooved surface with grooves ($P = 62 \, \mu\text{m}$). It can be observed
Figure 4: The front (F) and back (B) angles of the droplet of different volumes migrating in the longitudinal and transverse directions versus the fractional area ($A_F$) of the micro-grooved surface. The maximum error in front and back angles measurement is $\pm 2^\circ$. 
Figure 5: (a) Droplet images recorded in the longitudinal and transverse directions, when it is resting on a horizontal micro-grooved surface having grooves with $P = 62 \, \mu m$. (b) Droplet sliding mechanism when surface is tilted in the longitudinal direction. The high-speed camera is facing the transverse direction while recording these images. The multimedia view of the dynamics presented in this figure can be seen in supplementary movie 1.

that the diameter of the droplet is larger (by 0.52 mm) in the longitudinal view as compared to the view in the transverse direction. Inspection of Fig. 1 reveals that the structures on the surface is continuous in the longitudinal direction, but discontinuous in the transverse direction, which resembles a hill-valley type of of path. This results in anisotropic wetting and also leads to different sliding mechanisms of the droplet on an inclined micro-grooved surface in the longitudinal and transverse directions. These are explained in Fig. 5(b), Fig. 6 and Fig. 7.

Fig. 5 (b) shows the temporal evolution of a droplet of volume $12.7 \pm 0.9 \mu L$ sliding on
the micro-grooved surface with $P = 62 \, \mu\text{m}$ tilted at an angle $13^\circ$ (approximately) in the longitudinal direction. Here, the droplet is viewed in the transverse direction using the high-speed camera. The top panel in Fig. 5(b) shows the image of the droplet before 20 ms from the time its starts to sliding. In other words, time, $t = 0 \, \text{s}$ represents the time when the droplet starts sliding. We have reported time in the same way throughout this work. The droplet shape at $t = 0 \, \text{s}$ is shown in the middle panel of Fig. 5(b). Subsequently, the droplet slides down on the inclined micro-grooved surface. The droplet at $t = 5 \, \text{s}$ is shown in the bottom panel of Fig. 5(b). The solid red line and dotted blue line are drawn to mark the location of the front and back contact angle of the water droplet at $t = 0 \, \text{s}$. Close inspection of Fig. 5 reveals that the wetted diameter of the droplet remains constant (about $2.56 \, \text{mm}$) while sliding down the inclined micro-grooved surface. The value of the wetted diameter during the sliding is the same as that of the droplet diameter before the surface was inclined; Fig. 5(a). The wetted diameter of the droplet is denoted by two-headed arrows in Fig. 5(a) and (b).

The sliding behaviour of the droplet when the micro-grooved surface is tilted in transverse direction is investigated next. We observed two different sliding mechanisms of the droplet in this case, which are presented in Figs. 6 and 7.

Fig. 6 shows the time-sequenced images (from top to bottom panels: $t = -20 \, \text{ms}, 0 \, \text{ms}, 20 \, \text{ms}, 40 \, \text{ms}, 5 \, \text{s}$) of a droplet of volume $12.7 \pm 0.9 \, \mu\text{L}$ sliding on a micro-grooved surface with $P = 62 \, \mu\text{m}$, which is tilted at an angle $33^\circ$ in transverse direction. The insets in each panel represent the zoomed views near the the front and back contact angles. The red and white arrows in the insets show the initial locations of the back and front contact angles of the droplet, respectively. The wetted diameter of this droplet is approximately $2.05 \, \text{mm}$ while sliding on the surface. It can be observed that in this case, when droplet starts to slide, the advancing air-liquid interface rolls down and attaches with first incoming groove wall (in front of the droplet), which can be observed by comparing the inset images at time $20 \, \text{ms}$ and $0 \, \text{s}$. After this movement of the front contact angle with the incoming groove wall, the
Figure 6: Droplet migration when the micro-grooved surface with $P = 62 \mu m$ is tilted at an angle $33^\circ$ in transverse direction. The droplet is cleated using 21G needle. The high-speed camera is facing the longitudinal direction while recoding these images. The multimedia view of the dynamics presented in this figure can be seen in supplementary movie 2.

receding air-liquid interface detaches from the last groove wall (at the back of the droplet). The receding air-liquid interface does not move when the advancing air-liquid interface rolls to the nearest groove wall. This can be clearly observed at time 40 ms. Then again the advancing interface attaches to the next groove wall and subsequently the receding interface detaches from last groove wall. This type of “stick-slip” or “scrolling” motion is repeated as droplet slides downward on the micro-grooved surface with $P = 62 \mu m$.

In contrast, a droplet sliding on an inclined micro-grooved surface with $P = 76 \mu m$, exhibits a different type of sliding mechanism, which is depicted in Fig. 7. In this case the surface is
Figure 7: Droplet migration when the micro-grooved surface with $P = 76\mu m$ is tilted at an angle $30^\circ$ in transverse direction. The droplet is cleated using 21G needle. The high-speed camera is facing the longitudinal direction while recoding these images. The multimedia view of the dynamics presented in this figure can be seen in supplementary movie 3.

tilted at an angle $30^\circ$ in the transversed direction. In Fig. 7, the time-sequenced images of the droplet, while sliding on the inclined micro-grooved surface are shown at time -20 ms, 0 ms, 20 ms, 40 ms and 4 s. The wetted diameter of the droplet in this case is approximately 2.15 mm. The sliding mechanism in Fig. 7 is completely opposite to that observed in the previous case, shown in Fig. 6. It can be seen in Fig. 7 at time 20 ms that the receding air-liquid interface detaches from its contact point (at the back of the droplet). Then the advancing air-liquid interface attaches with the incoming groove wall (in front of the droplet) and droplet moves forward. This process gets repeated as the droplet slides down on the
surface. A similar mechanism of a droplet motion as shown in Fig. 7 was previously reported by Lv et al.\textsuperscript{10} for a droplet sliding on micro-textured surface having square pillars.

In the next section, we discuss the theoretical modelling of the two different sliding mechanisms of the droplet on micro-grooved surfaces.

**Theoretical modelling**

As explained in the previous section, two different mechanisms of droplet sliding behaviour on micro-grooved surfaces are observed depending on the direction of motion. The physical intuition is also different, thus we require different models to explain the motion of the droplet in the longitudinal and transversed directions, separately.

**Force-balance based model**

This model is mainly suitable to explain the sliding dynamics of the droplet in the longitudinal direction of a micro-grooved surface. In this model, the weight of the droplet is balanced by the surface tension force at the onset of the droplet sliding. Frenkel\textsuperscript{23} gave an approximate expression of sliding angle as a function of other parameters for a droplet sliding on a smooth surface. Later, this was also verified by Furmidge.\textsuperscript{22} A brief derivation of this is given below.

\begin{equation}
\rho g V \sin \alpha = \gamma_{LV} \left( \cos \theta_b - \cos \theta_f \right) w,
\end{equation}

where \( \rho \), \( V \) and \( \gamma_{LV} \) are the density, volume and surface tension at the liquid-solid interface, respectively. \( \alpha \), \( \theta_b \) and \( \theta_f \) are the sliding angle, the back and front angle of the droplet, respectively. \( w \) is the width of the droplet across the direction of sliding, which can be understood as the length of the droplet in contact with the surface. \( g \) is the gravitational acceleration. Fig. 8(a) shows the schematic diagram of a droplet moving in the direction of grooves or longitudinal direction. In this case, if surface is not grooved, \( w \) will be \( 2r_2, r_2 \).
being the radius of the droplet perpendicular to the direction of motion. However, in case of a grooved surface, \( w \) can be calculated as follows:

\[
w = 2r_2 - \frac{2r_2}{P} (P - a),
\]

(2)

where \( a \) is the width of the wall. Using Eq. (2) in Eq. (1), we obtain the sliding angle, \( \alpha \) of a droplet moving in the longitudinal direction of a micro-grooved surface, which is given by

\[
\alpha = \sin^{-1} \left[ \frac{2r_2 \gamma_{LV} (\cos \theta_b - \cos \theta_f)}{\rho g V} \left( 1 - \frac{P - a}{P} \right) \right].
\]

(3)

**Energy based model**

This model is suitable to calculate the sliding angle of the droplet migrating in the transversed direction of a micro-grooved surface. As explained above, when droplet moves in the transverse direction, it jumps from one wall to other. Therefore, when droplet detaches from the wall, surface energy of the droplet changes. A portion of droplet (liquid) area (\( \nabla S \)) which was in contact with solid surface previously, comes in contact with the air phase. This leaves the same area of the solid surface to be in contact with the air. This change energy
\(\nabla E\) can be expressed as: \(^{10}\)

\[
\nabla E = (\gamma_{SV} + \gamma_{LV} - \gamma_{SL}) \nabla S,
\]

(4)

where \(\gamma_{SV}\), \(\gamma_{LV}\) and \(\gamma_{SL}\) the surface energy per unit area (surface tension) of solid-air, liquid-air and solid-liquid interfaces, respectively. Fig. 8(b) shows the schematic diagram of a droplet moving in the transverse direction. Orange line denotes the movement of the receding interface of the droplet by \(\nabla x\), which results in an increase of liquid-air interfacial area (\(\nabla S\)) of the droplet. This area can be approximated as

\[
\nabla S = \nabla x r_1 \frac{a}{P},
\]

(5)

where \(r_1\) is the major radius of an elliptical droplet and \(a/P\) represents the fractional area of solid surface. Now, Using Young’s relation:

\[
\gamma_{LV} \cos \theta_s = \gamma_{SV} - \gamma_{SL},
\]

(6)

we get

\[
\nabla E = \gamma_{LV} (1 + \cos \theta_s) \nabla x r_1 \frac{a}{P},
\]

(7)

where \(\theta_s\) is the contact angle of the droplet on a smooth surface.

This change in surface energy must be balanced with the change in potential energy (\(\nabla U\)) of the droplet due to its downward movement. This can be expressed as follows assuming change in center of gravity of the droplet displaced by \(\nabla x/2\) due to \(\nabla x\) movement of the receding interface of the droplet, as also considered by Lv et al.: \(^{10}\)

\[
\nabla U = (\nabla x/2) \rho g V \sin \alpha.
\]

(8)
By equating Eqs. (7) and (8), we get

$$\sin \alpha = \frac{2r_1 \gamma_{LV} (1 + \cos \theta_s) \theta}{\rho g V} \frac{a}{P}.$$  

(9)

**Effect of pitch and droplet volume and comparison with the theoretical models**

We investigate the effects of size of the droplet on the sliding behaviour on micro-grooved surface with different pitches. The experimentally obtained sliding angles for different parameters are compared with the theoretical models when the droplets migrate in the longitudinal and transverse directions.

**Droplet sliding in the longitudinal direction**

Fig. 9(a) shows effect of droplet volume ($V$) on the sliding angle ($\alpha$) of a droplet on micro-grooved surfaces with different values of $P$. Here, the surface is inclined in such a way that the droplet migrates in the longitudinal direction of the grooves. For the lowest pitch considered ($P = 47\mu m$), it can be seen that the onset of the droplet sliding occurs for $V = 3.1\mu L$ at $\alpha = 26^\circ$. As we increase the value of the $P$, for the same volume of the droplet ($V = 3.1\mu L$) the sliding angle decreases to $\alpha = 22^\circ$ and $\alpha = 18.5^\circ$ for $P = 62\mu m$ and $P = 76\mu m$, respectively. It can be seen that as the volume of the droplet is increased from about $3.1 \mu L$ to $22.2 \mu L$, the corresponding sliding angle of the droplet decreased. This can be explained as follows. As the droplet volume increases, the gravitational force along the inclination in the downward direction increases, which in turn helps the droplet to move even at a smaller angle of inclination of the surface (lesser sliding angle). Also the surface tension force, which prevents the droplet sliding at the onset of motion, increases as the droplet size decreases. So there is a competition between the surface tension and gravitational forces. For small droplets, the surface tension force wins over the gravitational force for the same inclined surface. Thus, small droplets require higher inclination angle to start the motion
of the droplet. Recently, Abolghasemibizaki et al.\textsuperscript{14} investigated the effect of gravity on the rolling velocity of different size of droplets.

Inspection of the variations of the sliding angle with volume of the droplet for different values of $P$ migrating in the longitudinal direction shown in Fig. 9(a) reveals that increasing the pitch of the grooves of the surface decreases the sliding angle of a droplet. Increasing the value of $P$ leads to an increase in the hydrophobicity of the surface, which increases the contact angle of the droplet. This in turn reduces the component of surface tension force acting against the gravitational force (along the inclination of the surface). Thus the sliding angle of the droplet decreases as the pitch between the grooves is increased. For $P = 30\mu m$ and in case of smooth surface all the droplets considered do not slide for any angle of inclination. Thus, we can conclude that surfaces with $P < 30\mu m$ will behave similar to a smooth surface for the range of droplet sizes considered in the present study.

The sliding angles for different values of $P$ obtained from the theoretical model (Eq. 3) are shown by solid lines with the corresponding symbols in Fig. 9(a). Comparison of the theoretical and experimentally obtained results reveals that the theoretical model correctly predicts the experimentally observed trend in the variation of $\alpha$ versus $V$ for different values of $P$. However, quantitatively the results are different. This difference between the experimental and theoretical results can be attributed to the neglect of frictional forces between droplet and micro-grooved surfaces in the theoretical model.
Figure 9: The effect of droplet size on the sliding angle, $\alpha$ (in degree) for the droplet migrating in the (a) longitudinal direction and (b) transverse direction of the micro-grooved surface. The horizontal and vertical error bars are associated with droplet volume and sliding angle, respectively.

**Droplet sliding in transverse direction**

Next we investigate the droplet migration in the transverse direction on the micro-grooved surface for different values of $P$. In this case, after exceeding a critical value of the inclination
of the surface, the droplet moves in the transverse direction of the grooves of the micro-
grooved surface. The effect of droplet volume ($V$) on the sliding angle ($\alpha$) of a droplet on
micro-grooved surfaces having different pitch, $P$ when inclined in the transversed direction
is investigated in Fig. 9(b). It can be seen that for the lowest pitch considered ($P = 47\mu m$),
the onset of the droplet sliding occurs only for $V = 12.7\mu L$ at $\alpha = 51^\circ$. Smaller droplets
(volume $8.3\mu L$) does not slide at all for any value of the inclination angle. For $P = 62\mu m$ and
$P = 76\mu m$, the droplet of volume $8.3\mu L$ starts to slide for $\alpha = 64^\circ$ and $\alpha = 50^\circ$, respectively.
As expected, for all values of $P$, the sliding angle decreases with further increasing the size
of the droplet. However, it can be observed that sliding angle in case of transverse migration
for each set of parameters is much higher than that in case of the surface inclined in the
longitudinal direction of the grooves.

The theoretical results obtained using Eq. (9) for the transversed migration of the droplet
for different values of $P$ are shown by lines with the corresponding symbols. In this case, the
theoretical predictions of the sliding angles for different sets of parameters are better than
the longitudinal migration of the droplet. It can also be seen that the difference between
theoretical prediction and experimental results decreases with increase in the droplet size.
The friction force which has not been considered in the theoretical model, surface area
approximation and contact angle measurement contribute to this difference. However, the
trend in the variation of sliding angle with droplet volume for different values of $P$ has been
captured very well by the theoretical model.

Conclusions

The sliding dynamics of a water droplet of different volumes on micro-grooved surfaces
with three pitches, namely, $47\mu m$, $62\mu m$ and $76\mu m$ is investigated experimentally. The
micro-texture surfaces are prepared using photolithography technique on silicon wafer. The
influence of the pitch of the grooves, volume of the droplet and angle of inclined are varied to
study the droplet dynamics when it migrates in the direction longitudinal and transverse to the grooves. In case of the transverse migration, the mechanism of droplet motion is “stick-slip” or “scrolling” type as the droplet attaches and detaches from the groove walls as it moves in the downward direction. In case of the longitudinal migration, the droplet only slips without any intermediate change in the liquid-air interfacial area. We found that, for each set of physical parameters, when droplet migrates in the longitudinal direction of the micro-grooves, sliding angles are lower as compare that when it migrates in the transverse direction. It is also shown that increasing the droplet volume and the pitch of groove-walls decreases the sliding angle of the droplet. The theoretical models have been derived in accordance to the mechanism of sliding in the longitudinal and transverse directions. Although the theoretical models have been able to capture the trends and the physics observed in our experiments, we found some quantitative difference due to the simplifications and assumptions used in the models.

The present study provides fundamental insights into the wetting characteristics of anisotropic-textured surfaces, potentially useful to design self-cleaning and low drag surfaces. The anisotropic behavior of micro-grooved surface can also be utilized to create unidirectional sliding surface, in which droplets can be made to slide in a desired direction.

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