ISSN 2179-3956

THE PHENOMENON OF THERMO-CAPILLARY MIGRATION EFFECTED BY SURFACE MICRO-GROOVES*

Qingwen Dai[1]
Wei Huang[2]
Xiaolei Wang[3]

Abstract

The Marangoni effect is an important phenomenon where a surface tension gradient drives liquid towards high surface tension regions. Temperature gradient, evaporation, disparity of viscosity, and surface roughness and topography are all significant factors that can affect this thermo-capillary migration. The purpose of this study was to investigate the influence of micro-groove patterns on the migration of paraffin oil, and obtain a well-designed texture of micro-grooves to prevent the thermo-capillary migration. Patterns of micro-grooves with differing orientations and geometric parameters were fabricated on the surface of SUS 316 stainless steel substrates. Experiments on the migration behavior with different viscosities of paraffin oils were carried out various temperature gradients. The experimental phenomena indicated that the surface with the micro-grooves perpendicular or parallel to the temperature gradient have a strong impact on the migration performance of paraffin oil. Micro-grooves perpendicular to the temperature gradient exhibited extraordinary slower migration velocity than that of the parallel one. Width and depth of micro-grooves had an obvious influence on the behavior of temperature-driven migration and detail discussions on the effects of these geometric parameters were carried out.

Keywords: Thermo-capillary migration; Temperature gradient; Micro-grooves; Orientation

[1] *Doctoral candidate, College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics & Astronautics, Nanjing, Jiangsu, China.*

[2] *Professor, College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics & Astronautics, Nanjing, Jiangsu, China.*

[3] *Professor, College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics & Astronautics, Nanjing, Jiangsu, China.*

* *Technical contribution to the 2nd International Brazilian Conference on Tribology – TriboBR 2014, November 3rd to 5th, 2014, Foz do Iguaçu, PR, Brazil.*

ISSN 2179-3956

1 INTRODUCTION

The Marangoni effect, also known as "tears of wine", was named after Italian physicist C. Marangoni. In a wine glass, evaporating alcohol creates inhomogeneous alcohol concentrations that generate a gradient in the wine surface tension and produce a traction that raises the wine up the glass wall to form a thin film. The film eventually converges into a droplet and falls back into the wine like a tear [1]. Marangoni performed a detailed investigation on this phenomenon and determined the surface tension gradient generated by variations in either the composition or temperature along a free surface drives liquid towards regions of high surface tension without any external force [2]. In the 20th century, Levich concentrated on the theoretical analysis of this surface-tension-driven movement and ascertained that increasing the surface concentration of the surface active species decreased the surface tension. Surface tension gradients formed between compressed and uncompressed areas and migration occurred [3]. Therefore, the surface tension gradient of a free surface causes this movement, i.e., thermo-capillary migration [4].
Thermo-capillary migration can be induced by temperature gradients at a surface or concentration differences in a liquid. Fote et al. investigated the migration of hydrocarbon thin films under temperature gradients with different surface finishes. The results demonstrated that temperature gradients could drive the migration of thin liquid films from warm to cold areas [5]. Hu and Larson performed a theoretical study on what effects Marangoni stress had on the flow of an evaporating droplet; his results revealed that latent evaporation energy broke the free surface boundary and produced thermal gradients that generated Marangoni stresses and a subsequent internal flow [6].
Other mechanisms than the aforementioned temperature induced surface tension gradients in liquids impel this migration. The radius of curvature for a micro-rough surface varies with depth and can cause a variation in the surface tension and drives a liquid to spread across the surface akin to capillary action, which means the surface topography influences liquid migration behavior [7]. Klien et al. experimented on the migration of oil drops on both grounded and grinded surfaces with scratches angled against the temperature gradient and found the surface topography more strongly influenced the oil migration [8]. Our previous preliminary research demonstrated that the surface roughness and grinding scar orientation strongly influenced the migration behavior [9]. Recently, Karapetsas investigated the thermocapillary-driven spread of a droplet with a non-monotonic surface tension dependence on the temperature and differentiated the migration behavior of ordinary and self-rewetting fluids [10].
Thermo-capillary migrations have been experimentally and theoretically researched for centuries [11-14]. This movement plays an important role in the fundamental physics of interfacial flows [15,16] and enables fascinating industrial applications, such as in hard disk technology, inkjet printing, microfluidics, and micro-electronics [17,18]. Moreover, this phenomenon should be carefully considered for idiosyncratic applications, for instance, space lubrication industries, where the temperature changes from -60 °C to 200 °C and lubricant film migration strongly affects the device performance [19-21]. For most liquid lubricants employed in mechanical devices for use in space, frictional heat generated via asperities on the tribological surfaces of the moving element can create a temperature gradient between the contact area and surroundings, which changes the liquid lubricant's surface tension and ultimately causes the lubricants to migrate from the contact area to a relatively lower-

ISSN 2179-3956

temperature area [22]. Under these conditions, surface-tension-driven forces are one of the most significant factors affecting the lubricant flow and even lubrication failure. Therefore, controlling the migration is necessary to guarantee the lubricant lifetime for moving mechanisms in space [23].
Physical phenomena generally involve an energy exchange and/or signal transmission at the surface. Investigations on the surface phenomenon, particularly on the micro- and nanometer scale, have motivated the design of surfaces with novel or combinative functions [24]. Over the last decade, surfaces have been structured, textured or engineered to provide particular functions in many industrial applications [25-27]. The surface texture can help preserve lubricant, prevent seizure, trap wear debris to decrease further wear, and, particularly, provide additional hydrodynamic effects to increase the load carrying capacity of parallel sliding surfaces, with decreasing friction and wear for sliding bearings, mechanical seals and engine components being the dominant use for surface textures.
Meanwhile, lubricant must be maintained on the rubbing surface. As mentioned above, most surface textures are designed for tribological purposes. However, what affect does the surface texture have on the thermally driven migration of the lubricant? Will the arrayed surface structures accelerate or obstruct the migration velocity? Further research is necessary to investigate these effects. Therefore, this paper studies what affect micro-grooves and oil viscosity have on the thermo-capillary driven migration behavior under various temperature gradients. Furthermore, special attention is paid to the influence of different geometric parameters and micro-groove orientations relative to the temperature gradients. A well-designed micro-groove surface that significantly prevents the thermo-capillary migration of the lubricant should be obtained.

2 EXPERIMENTAL

2.1 Apparatus

Figure 1 shows a schematic diagram for the apparatus used in this study. Aluminum was chosen as the block heat conduction material. Two temperature-controlled aluminum blocks were fixed on a horizontal platform. One block could be heated to the desired temperature using an embedded ceramic plate heater. The other block was immersed in ice water to maintain a constant temperature of 0°C. A metal specimen was placed between the cooling and heating blocks. The two ends of the metal substrate were tightly attached to the blocks to achieve good thermal conductivity. By simultaneously controlling the cooling and heating blocks, a temperature gradient could be generated along the length of the metal substrate.

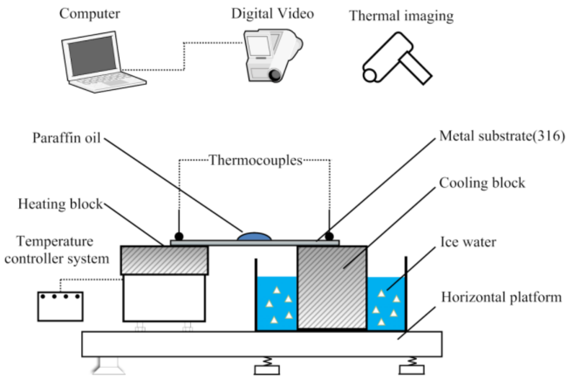

Figure 1. Schematic diagram of the experimental apparatus.

* *Technical contribution to the 2nd International Brazilian Conference on Tribology – TriboBR 2014, November 3rd to 5th, 2014, Foz do Iguaçu, PR, Brazil.*

A thermal imaging acquisition device (Fluke, USA) and thermocouples were used to obtain the real-time temperature distribution at the sample surface. A digital video camera was used in this experiment to monitor the dynamic liquid migration process. Key frames from this video were then extracted to calculate the migration velocity using image and video editing software.

2.2 Specimen fabrication

As shown in Figure 1, the paraffin oil migration experiments were performed on a metal substrate. All specimens were made of 76 mm×30 mm×3 mm SUS 316 stainless steel. Each test surface was manufactured by sequentially grinding and polishing to obtain a final surface roughness, Ra, ranging from 10-20 nm and a high degree of flatness. Next, arrayed micro-grooves with different parameters were fabricated on the surface via photolithography combined with an electrolytic etching process as mentioned in [28, 29]. These processes could precisely control the micro-feature dimensions and orientations without any surface abrasion in an undesired area. The surface roughness and geometric dimensioning described in this article were measured using a surface mapping microscope (Rtec instruments, USA). Table 1 lists the geometric parameters for the studied patterns. Figure 2(a) shows a typical surface topography for micro-grooves 200-µm wide and 22-µm deep running parallel to the substrate length, and Figure 2(b) shows the surface with perpendicular micro-grooves 100-µm wide and 60-µm deep. The area density (r) was defined as the ratio between the areas for one groove and between two neighboring grooves. As illustrated in Figure 2, this value can be calculated as *w/l.*

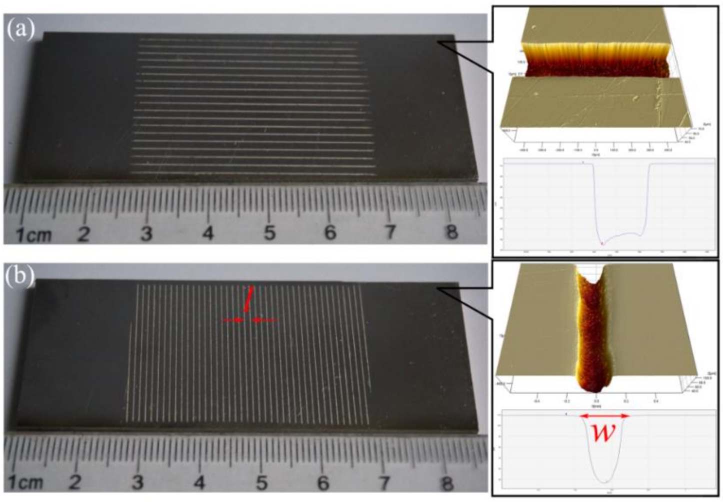

Figure 2. Photographic and 3D topographic images of the substrate surfaces: (a) micro-grooves parallel to the substrate length and (b) micro-groove perpendicular to the substrate length.

Table 1. Geometric parameters of micro grooves on the substrate surface

Specimen no.	Width *w* (μm)	Depth *h* (μm)	Pitch *l* (μm)	Area density *r* (%)	orientation
1	0	0	0	0	smooth
2	100	20~22	1000	10	parallel
3	200	20~22	2000	10	parallel
4	300	20~22	3000	10	parallel
5	300	59~61	3000	10	parallel
6	100	20~22	1000	10	perpendicular
7	100	59~61	1000	10	perpendicular
8	200	20~22	2000	10	perpendicular
9	300	20~22	3000	10	perpendicular

* *Technical contribution to the 2nd International Brazilian Conference on Tribology – TriboBR 2014, November 3rd to 5th, 2014, Foz do Iguaçu, PR, Brazil.*

ISSN 2179-3956

2.3 Test Procedure

To rule out any effects additives have on the oil migration, paraffin oils with different kinematic viscosities obtained from crude oil fractionation were used for all experiments. The kinematic viscosities were all obtained under a constant temperature of 40ºC using an ubbelohde viscometer, which is a capillary based viscosity measurement. A microliter syringe was used to precisely control the paraffin oil quantity. In addition, a scale plate was fixed onto the aluminum cooling block near the specimen to ensure the paraffin oil droplets were always placed at the same location. Before these experiments, each specimen was sequentially ultrasonically cleaned in acetone and alcohol, rinsed with deionized water, and finally blow-dried with nitrogen. Our preliminary research demonstrated the temperature gradient is nearly linear along the length of the substrate [9]. The average of the temperature gradient along the substrate surface was used in this experiment, and the main test conditions are listed in Table 2.
Four groups of experiments were performed to determine what influence the geometric parameters and micro-groove orientation had on the migration behavior. These experimental groups focused on the effects of the (1) viscosity, (2) width, (3) depth and (4) orientation.

Table 2. Experimental conditions

Environment temperature:	19–21°C
Experimental lubricant:	paraffin oil
Temperature gradient:	0.6–3 °C/mm
Kinematic viscosity:	5.7–56.6 mm^2/s
Volume of oil:	5 μL

3 RESULTS

Figure 3(a) shows a typical paraffin oil migration process (19.1 mm^2/s kinematic viscosity at 40ºC) on a surface with micro-grooves arrayed parallel to the 2.2 ºC/mm temperature gradient. This merged image contains 8 video frames with a time interval of 3 seconds. The paraffin oil was dropped at the same starting position on the warm side and permitted to migrate under the temperature gradient for 20 mm generally towards the cold side in most case. The migration distance was measured at the front edge of the droplet, and the migration velocity was calculated using the mean distance in the following figures. A detailed migration velocity for various viscosities and temperature gradients at the surface is shown in Figure 3(b). The migration velocity increased with an increasing temperature gradient. As the viscosity increased, the migration decreased. The Paraffin oil with the highest kinematic viscosity (53.6 mm^2/s at 40ºC) exhibited the lowest migration velocity in this experiment.

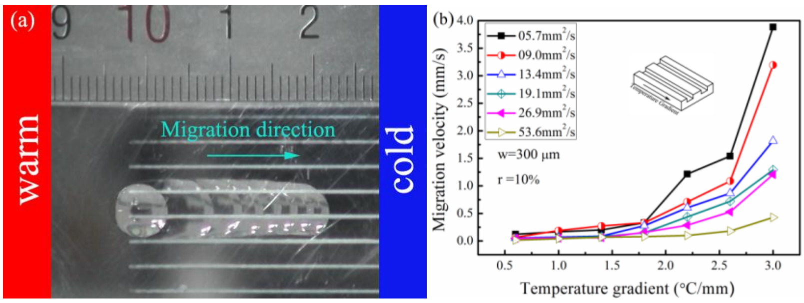

Figure 3. (a) Detailed migration behavior at a time interval of 3 seconds. (b) The effects of viscosity and temperature gradient on the average migration velocity over a distance of 20 mm.

** Technical contribution to the 2nd International Brazilian Conference on Tribology – TriboBR 2014, November 3rd to 5th, 2014, Foz do Iguaçu, PR, Brazil.*

ISSN 2179-3956

Previous research indicated the ground surface orientation significantly influences the migration behavior [9]. Therefore, experiments investigating the micro-groove orientation effect on the paraffin oil migration velocity were performed. Figure 4 presents the migration velocity on an untextured surface and one with parallel and perpendicular grooves under different temperature gradients and viscosities. When the temperature gradient was below 1ºC/mm, the migration velocities of these three specimens differed only slightly. After increasing the temperature gradient to 3ºC/mm for paraffin oil with a viscosity of 26.9 mm^2/s, the parallel grooved surface exhibited the highest migration velocity, 3.0 mm/s, which nearly tripled the untextured surface (approximately 1.0 mm/s), while the velocity for the perpendicularly grooved surface was only approximately 0.4 mm/s, which is less than half the untextured surface. These results indicate increasing the temperature gradient makes the surface texture influence evident, and surfaces with parallel grooves exhibit higher relative migration velocities, while perpendicular grooves provide the lowest migration velocity. In other words, micro-grooves perpendicular to the temperature gradient obstruct thermally driven migration, while parallel ones accelerate it.

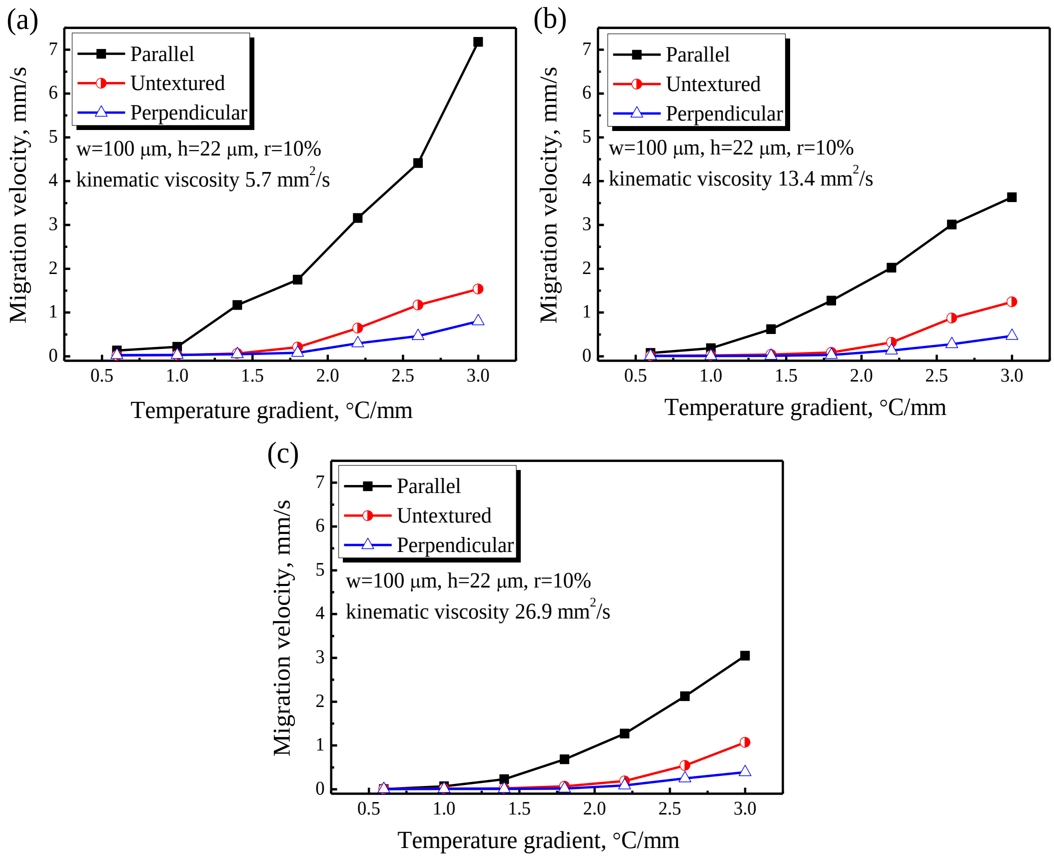

Figure 4. Effect of the micro-groove orientation on the migration behavior at different temperature gradients and viscosities of: (a) 5.7 mm^2/s, (b) 13.4 mm^2/s and (c) 26.9 mm^2/s

The influence of the groove depth on the migration behavior was demonstrated as follows. Figure 5 shows the effect of depth for a groove parallel to the temperature gradient. Temperature gradients of 1.4, 2.2 and 3.0ºC/mm and paraffin oil with viscosities of 5.7, 13.4, 26.9 and 53.6 mm^2/s were used in these tests. As shown in Figure 5(a), a temperature gradient of 1.4 ºC/mm yields a low migration velocity for these three specimens. After increasing the temperature gradient to 2.2 ºC/mm, as shown in Figure 5(b), with an oil kinematic viscosity of 5.7 mm^2/s, micro-grooves with a depth of 22 µm exhibited approximately 200% higher migration velocities than an

* *Technical contribution to the 2nd International Brazilian Conference on Tribology – TriboBR 2014, November 3rd to 5th, 2014, Foz do Iguaçu, PR, Brazil.*

ISSN 2179-3956

untextured surface, and the migration velocity at a depth of 60 µm was as high as 2.0 mm/s. These results mean that the migration velocity of a surface with grooves parallel to the temperature gradient increases with increasing depth. Once the viscosity was increased to 53.6 mm^2/s, the migration velocities were nearly identical, which means that increasing the viscosity makes the influence of depth insignificant. A comparison between Figure 5 (a), (b) and (c) indicates the influence from depth is similar for the three temperature gradients.

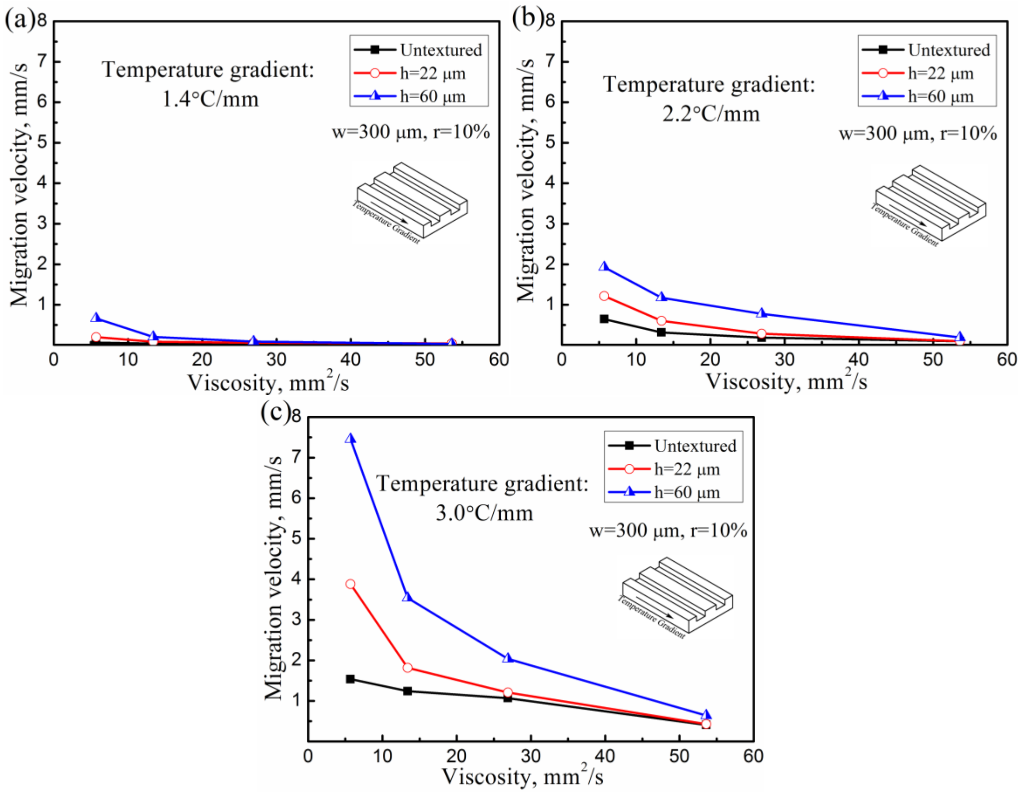

Figure 5. Effect of depth on the paraffin oil migration velocity for surfaces with parallel grooves at temperature gradient ∇T: (a) ∇T =1.4 ºC/mm, (b) ∇T =2.2 ºC/mm and (c) ∇T =3.0 ºC/mm.

The influence of depth when the groove is perpendicular to the temperature gradient is shown in Figure 6. As shown in Figure 6(b), a temperature gradient of 2.2 ºC/mm with a paraffin oil viscosity of 5.7 mm^2/s yields a migration velocity for the untextured surface of approximately 0.65 mm/s, which is much higher than for the texture surface, while the velocity for 60-µm deep micro-grooves was the lowest. Obviously, the migration velocity increased with decreasing depth when the grooves are perpendicular to the temperature gradient. The migration velocity trends for the three temperature gradients are similar. Thus, the groove depth effects can be summarized as follows: for parallel grooves, it contributes to this migration, while for the perpendicular grooves, increasing the depth prevents the thermally driven migration.

ISSN 2179-3956

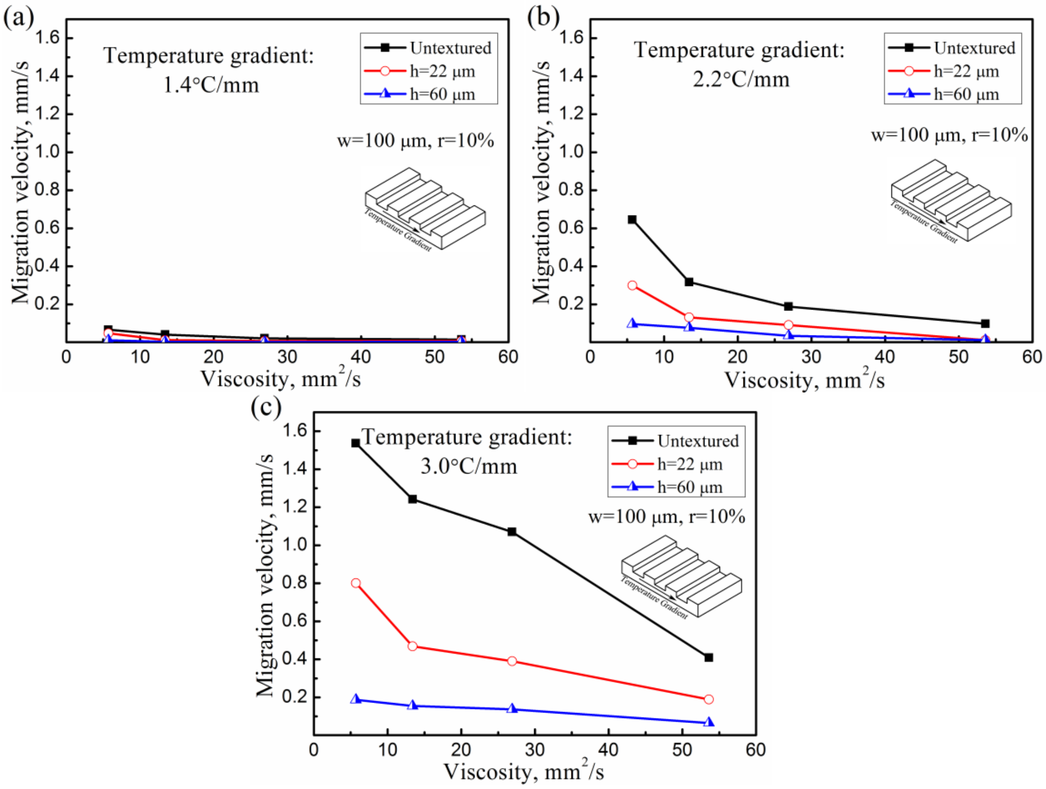

Figure 6. The effect of depth on the migration velocity of paraffin oil on the surface with perpendicular grooves at temperature gradient ∇T: (a) ∇T =1.4 ºC/mm, (b) ∇T =2.2 ºC/mm and (c) ∇T =3.0 ºC/mm.

The width is an important geometric micro-groove parameter. The effect of width on the migration behavior for grooves parallel to the temperature gradient is shown in Figure 7. Specimens 100, 200, and 300 µm wide were tested. When the oil viscosity was 5.7 mm^2/s, the 100-µm wide specimen exhibited the fastest migration velocity, approximately 7.17 mm/s (see Fig. 7a), and the migration velocity dropped with increasing width. Increasing the viscosity decreased the difference in migration velocities for these three specimens. As shown in Figure 7(d), the migration velocities of specimens of No. 3 (w 200 µm) and No. 4 (w 300 µm) were too low to differentiate when the oil kinematic viscosity was 53.6 mm^2/s.

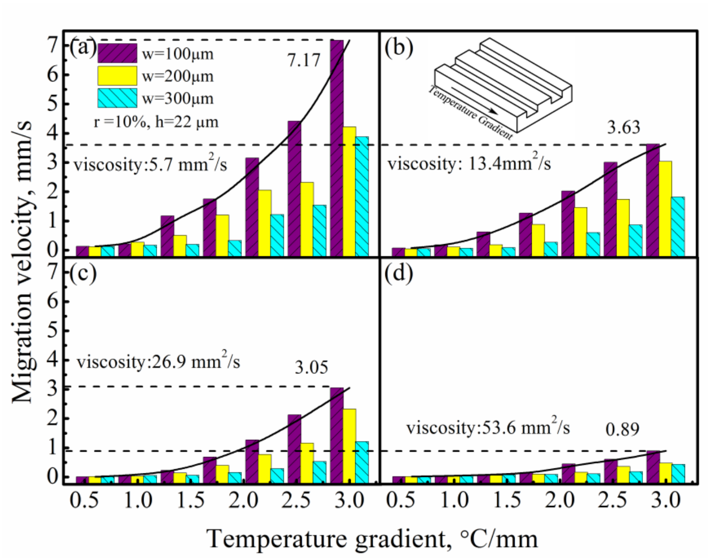

Figure 7. Effect of parallel the micro-groove width on the migration behavior with viscosities of: (a) 5.7 mm^2/s, (b) 13.4 mm^2/s, (c) 26.9 mm^2/s and (d) 53.6 mm^2/s.

** Technical contribution to the 2nd International Brazilian Conference on Tribology – TriboBR 2014, November 3rd to 5th, 2014, Foz do Iguaçu, PR, Brazil.*

ISSN 2179-3956

Figure 8 shows the migration velocity for specimens with different groove widths. The micro-groove dimensions were the same as in Figure 7, with the only difference being the grooves were perpendicular to the temperature gradient. Increasing the temperature gradient clearly increased the migration velocity. Only a small difference existed between the migration velocities for these three specimens, and increasing the oil viscosity decreased these differences. As shown in Figure 8(d), the migration velocities were nearly identical when the oil kinematic viscosity was 53.6 mm^2/s.

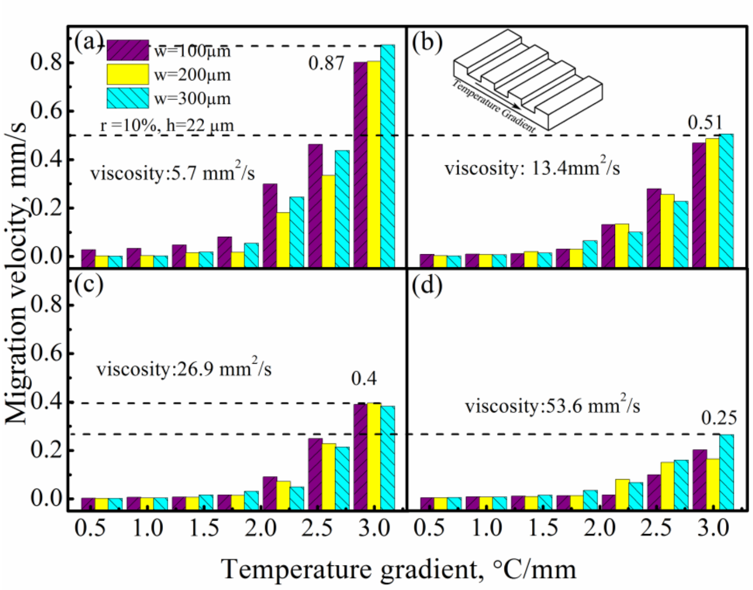

Figure 8. Effect of the perpendicular micro-groove width on the migration behavior with viscosities of: (a) 5.7 mm^2/s, (b) 13.4 mm^2/s, (c) 26.9 mm^2/s and (d) 53.6 mm^2/s.

Figure 9(a) shows the merged image of 14 video frames. It demonstrates the detailed migration process on a smooth surface at a temperature gradient of 3.0ºC/mm. When paraffin oil (5.7 mm^2/s viscosity, at 40ºC) was dropped on the surface, a thermally driven migration occurred in the direction of the temperature gradient accompanied by diffusion vertical to the temperature gradient, which spread the liquid into a film. An interesting phenomenon in the migration process emerged when the film-like paraffin oil contracted back into the shape of a droplet before migrating. Figure 9(b) details the experimental process for a specimen with micro-grooves parallel to the temperature gradient for a 5.7 mm^2/s viscosity and 3ºC/mm temperature gradient. A thermally driven migration in the groove direction occurred. During this process, the diffusion and contraction phenomena were also observed.

ISSN 2179-3956

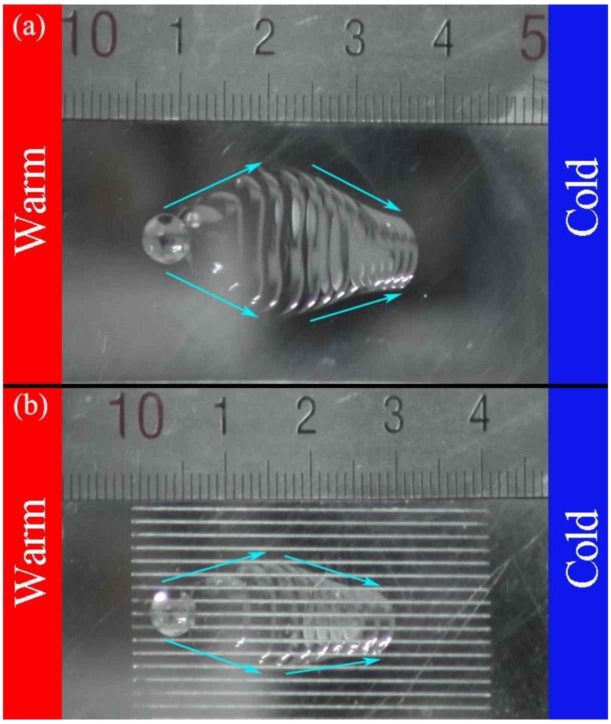

Figure 9. Detailed thermally driven migration process for an (a) untextured surface and (b) surface with parallel grooves under a temperature gradient of 3.0 ºC/mm.

4 DISCUSSION

For a gas-liquid-solid system under dynamic conditions, the force balance in the vicinity of the three-phase contact line is between gravitational, capillary, and van der Waals forces and the opposing viscous friction of the advancing or receding liquid [30]. Figure 10 shows that placing a sessile droplet on a surface creates three interfacial tensions γ_{LV}, γ_{SL}, γ_{SV} in the vicinity of the three-phase contact line, where γ_{LV}, γ_{SL}, γ_{SV} are the liquid-vapor, solid-liquid and solid-vapor interfacial tensions, respectively. To better understand the interfacial tension, it was defined as the force per unit length [31]. The interfacial tension force balance from Young's equation [32]:

$$\gamma_{SV} = \gamma_{SL} + \gamma_{LV} \cos\theta \quad (1)$$

where θ is the equilibrium contact angle of the drop on the surface.

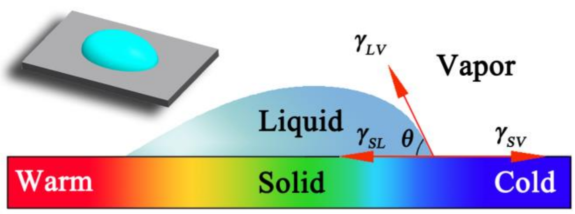

Figure 10. Interfacial tension at the three-phase contact line for a sessile droplet.

Liquid migration is known to occur in the direction of a temperature gradient, i.e., from warm to cold regions. Figure 3 shows the migration velocity for paraffin oil with differing viscosities as the temperature gradient is increased. As the temperature increased, the interfacial tensions γ_{LV} and γ_{SL}, in the droplet decreased, which produced traction on the droplet surface to migrate towards the cold side. Meanwhile, the hydrodynamic resistance of the liquid increased with increasing viscosity, which increased the resistance relative to the low-viscosity oil. These experimental results

** Technical contribution to the 2nd International Brazilian Conference on Tribology – TriboBR 2014, November 3rd to 5th, 2014, Foz do Iguaçu, PR, Brazil.*

ISSN 2179-3956

confirmed that higher oil viscosities exhibit lower migration velocities, which indicates high-viscosity oil is an effective method for preventing thermally driven migration.

The surface texture plays an important role in the migration process. Figure 11 shows a diagram of the oil migrating over a groove perpendicular to the temperature gradient. Ignoring the temperature influence allows the inner pressure of a drop can be estimated as [4]:

$$P = P_0 + \gamma / R \quad (2)$$

where P is the inner pressure of the drop, P_0 is the outer pressure of the drop, R is the interfacial radius of curvature for the drop, and γ is the surface tension of the drop.

The differential form of equation (2) is:

$$\frac{dP}{dx} = \frac{d\gamma}{Rdx} - \frac{\gamma}{R^2}\frac{dR}{dx} \quad (3)$$

Because the temperature influence is ignored along with the temperature gradient induced traction, the pressure gradient in the droplet is obtained:

$$\frac{dP}{dx} = -\frac{\gamma}{R^2}\frac{dR}{dx} \quad (4)$$

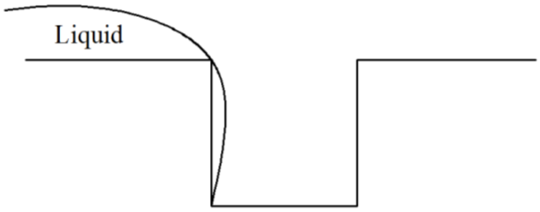

Figure 11. Diagram for oil migrating over a groove perpendicular to the temperature gradient.

This equation indicates a pressure gradient would be produced when the paraffin oil migrates at a right-angle to the groove and the inner pressure is larger near an edge than far from it. Hence, a pressure gradient emerges and produces energy that obstructs the paraffin droplet migration over the groove. Additionally, deepening the groove depth increases this hindering energy relative to a shallower groove.

The results shown in Figure 4 demonstrate this strong structural anti-effect on the migration process. The surface with perpendicular micro-grooves exhibited the lowest migration velocity, which was half of the smooth surface because these micro-grooves consist of the structure shown in Figure 11; therefore, these obstructions accumulate and decrease the migration velocity. Figure 6 shows the affect perpendicular grooves depth has on the migration behavior. These results verify depth plays an important role in the migration, increasing the depth decreases the migration velocity, which means deepening the micro-grooves will better impede the migration.

The surface texture for micro-grooves perpendicular to the temperature produces a barrier to thermally driven flow, while the migration velocity for parallel grooves is higher than for the untextured surface. Thus, an interesting question is why a surface with parallel grooves is faster than an untenured one. Figure 12 shows a schematic diagram for droplet migration on a surface with grooves parallel to the temperature gradient. These micro-grooves change the contact angle, θ, of the droplet relative to an ideal smooth surface, which changes the γ_{LV} component in the horizontal

* *Technical contribution to the 2nd International Brazilian Conference on Tribology – TriboBR 2014, November 3rd to 5th, 2014, Foz do Iguaçu, PR, Brazil.*

ISSN 2179-3956

direction. Furthermore, the micro-grooves can act as micro-capillaries parallel to the temperature gradient, which produces an extra force, $F_{capillary}$, that increases the migration velocity in the temperature gradient direction.

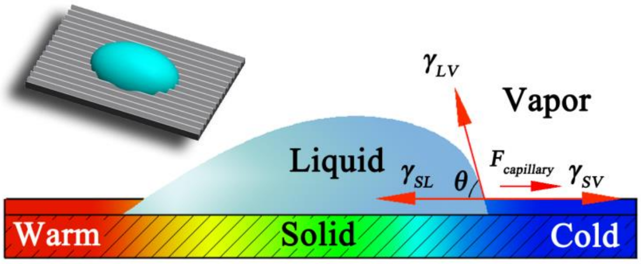

Figure 12. Interfacial tension at the three-phase contact line force for a sessile droplet on a surface with micro-grooves parallel to the temperature gradient.

Also, we can intuitively understand why the migration velocity on a surface with micro-grooves parallel to the temperature gradient is the fastest. For parallel grooves, the thermally driven migration occurs along the temperature gradient accompanying the perpendicular diffusion of the paraffin oil like a liquid film. The experimental phenomenon shown in Figure 9 confirms the micro-grooves impede this diffusion process and promote the paraffin oil converging into these grooves, which increases the velocity relative to a smooth surface. Additionally, increasing the depth further inhibits the diffusion process; therefore, the migration velocity increases. The experimental results shown in Figure 5 demonstrate this effect, and the migration velocity increased with increasing groove depth when parallel to the temperature gradient.
Experiments confirming the width effects were performed. The results in Figure 7 for a surface with parallel grooves indicate narrow grooves achieve faster migration velocities. This can be explained by considered the parallel grooves to be micro-capillaries parallel to the temperature gradient. The narrower the micro-grooves are, the more significant the capillarity effect will be. In other words, this extra force, $F_{capillary}$, increased with increasing depth or decreasing width, which increased the migration velocity. However, for a surface with perpendicular grooves, the width plays an insignificance role on the migration behavior. The structure shown in Figure 12 indicates increase the grooves width does not change the energy obstructing the paraffin droplet migration, which may be the reason the migration velocities for a perpendicularly grooved surfaces with different widths were nearly identical as shown in Figure 8. However, there could be a channel size with a certain width and depth in which the droplet will be literally stuck. Further research into the aspect ratio between the droplet diameter and groove width could be particularly interesting.
Interestingly, the liquid maintained the normal sharp shape shown in Figure 3(a) while spreading in the vertical direction during the migration process as shown in Figure 9 because the local temperature at the starting position where the drop was placed differed in these two situations. The local temperature was higher for Figure 9 than Figure 3(a). Furthermore, the paraffin oil viscosity used in Figure 9 was lower than for Figure 3(a); therefore, the hydrodynamic resistance of the paraffin oil was weaker. These parameters resulted in the different diffusivities of the droplet. Another question is why the paraffin oil droplets contract during the migration process, as shown in Figure 9. Liquid migration occurs in the direction of a temperature gradient, i.e., from warm to cold areas. In this study, the temperature decreased during the migration process, which increased the viscosity and solid-liquid interfacial tension,

γ_{SL}, of the droplet. Therefore, the droplet diffusion process in the direction perpendicular to the temperature gradient was impeded, and the paraffin oil returned to the shape of a droplet.

In all experiments, the kinematic viscosity of the droplet was connected to its inner temperature. An ubbelohde viscometer instrument was used to measure the different kinematic viscosities of the paraffin oil with increasing temperature. The viscosity-temperature performance was determined; therefore, we considered $\eta(T)$ to be the paraffin oil viscosity at temperature T. The migration velocity was generally proportional to the temperature gradient, ∇T, and inner temperature, T, of the droplet and inversely proportional to the viscosity, $\eta(T)$.

We measured the migration process every second for four groups of experiments using a smooth surface: (1) temperature gradient of 2.2 ºC/mm, viscosity of 5.7 mm^2/s; (2) temperature gradient of 2.6 ºC/mm, viscosity of 5.7 mm^2/s; (3) temperature gradient of 3.0 ºC/mm, viscosity of 5.7 mm^2/s; and (4) temperature gradient of 3.0 ºC/mm, viscosity of 13.4 mm^2/s. By measuring the oil migration distance every second, the average migration velocity and droplet temperature at different locations could be obtained. The relationship between the migration velocity, V, and $\frac{\nabla T \cdot T}{\eta(T)}$ is as shown Figure 13.

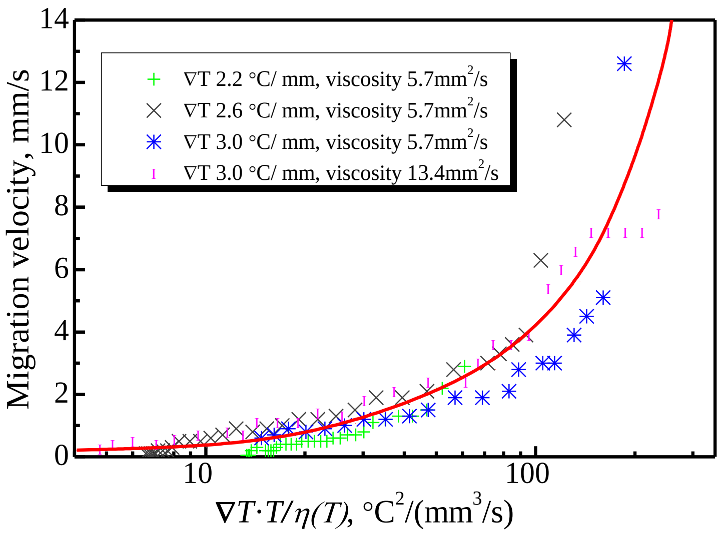

Figure 11. Experimental results and trend curves for the migration velocity on a smooth surface.

The migration velocity trends achieved under different experimental conditions were similar. From these results, the migration velocity of paraffin oil with a known viscosity on a smooth surface might be predicated based on the temperature gradient and location. Of course, further impact factors should be explored to explain the differences between the different data sets and make this curve more applicable.

5 CONCLUSION

In this study, experiments investigating the effects of micro-groove orientation and geometric parameters on the thermally driven migration of paraffin oil were performed. The following conclusions were drawn from this study:

1. The groove orientation on the surface plays an important role in the migration behavior. Relative to smooth and parallel grooved surfaces, micro-grooves perpendicular to the temperature gradient effectively prevented oil migration.

* *Technical contribution to the 2nd International Brazilian Conference on Tribology – TriboBR 2014, November 3rd to 5th, 2014, Foz do Iguaçu, PR, Brazil.*

ISSN 2179-3956

2. When the micro-grooves are perpendicular to the temperature gradient, increasing the grooves depth better prevents the thermally driven migration. Increasing the depth of parallel grooves enhanced this migration.
3. For micro-grooves parallel to the temperature gradient, the migration velocity decreases with increasing width. For perpendicular grooves, the width is irrelevant to the migration behavior.
4. For the smooth surface, the migration velocity for a paraffin oil droplet with a known-viscosity might be predicated on the temperature gradient and location.

Acknowledgments

The authors are grateful for the financial support provided by the National Natural Science Foundation of China (Nos. 51105199 and 51175246), Funding of Jiangsu Innovation Program for Graduate Education (No. KYLX_0239), and the Fundamental Research Funds for the Central Universities.

REFERENCES

1 Pearson JRA. On convection cells induced by surface tension. J Fluid Mech. 1958; 4(5):489-500.
2 Scriven LE, Sternling CV. The Marangoni effects. Nature. 1960; 187:186-188.
3 Levich VG, Krylov VS. Surface-tension-driven phenomena. Annu Rev Fluid Mech. 1969; 1:293-316.
4 Adamson AW. Physical Chemistry of Surface. 1nd. New York: Wiley-Interscience; 1960.
5 Fote AA, Slade RA, Feuerstein S. Thermally induced migration of hydrocarbon oil. J Lubr Technol. 1977; 99(2):158-162.
6 Hu H, Larson RG. Analysis of the effects of marangoni stresses on the microflow in an evaporating sessile droplet. Langmuir. 2005; 21(9):3972-3980.
7 Roberts EW, Todd MJ. Space and vacuum tribology. Wear. 1990;136(1):157-167.
8 Klien S, Surberg CH, Stehr W. Temperature diven lubricant migration on tribological surface. Ectribology. 2007:637-647.
9 Dai QW, Huang W, Wang XL. Surface roughness and orientation effects on the thermo-capillary migration off a droplet of paraffin oil. Exp Therm Fluid Sci. 2014; 57:200-206.
10 Karapetsas G, Sahu KC, Sefiane K, Matar OK. Thermocapillary-driven motion of a sessile drop: effect of non-monotonic dependence of surface tension on temperature. Langmuir. 2014; 30(15):4310-4321.
11 Ford ML, Nadim A. Thermocapillary migration of an attached drop on a solid surface. Phys Fluids. 1994; 6(9):3183-3185.
12 Smith MK. Thermocapillary migration of a two-dimensional liquid droplet on a solid surface. J Fluid Mech. 1995; 294:209-230.
13 Wasan DT, Nikolov AD, Brenner H. Droplets speeding on surfaces. Science. 2001; 291(5504):605-606.
14 Daniel S. Fast drop movements resulting from the phase change on a gradient surface. Science. 2001; 291(5504):633-636.
15 Vanhook SJ, Schatz MF, Swift JB, Mccormick WD, Swinney HL. Long-wavelength surface-tension-driven Benard convection: experiment and theory. J Fluid Mech. 1997; 345:45-78.
16 VanHook SJ, Schatz MF, Mccormick WD, Swift JB, Swinney HL. Long-wavelength instability in surface-tension-driven Benard convection. Phys Rev Lett. 1995; 75(24):4397-4400.
17 Bonn D, Eggers J, Indekeu J, Meunier J, Rolley E. Wetting and spreading. Rev Mod Phys. 2009; 81(2):739-805.

* *Technical contribution to the 2nd International Brazilian Conference on Tribology – TriboBR 2014, November 3rd to 5th, 2014, Foz do Iguaçu, PR, Brazil.*

ISSN 2179-3956

18 Langevin D, Monroy F. Marangoni stresses and surface compression rheology of surfactant solutions. Achievements and problems. Adv Colloid Interface Sci. 2014; 206:141-149.
19 Zaretsky EV. Liquid lubrication in space. Tribol Int. 1990;23(2):75-93.
20 Cheng T, Zhao B, Chao J, Meeks SW, Velidandea V. The lubricant migration rate on the hard disk surface. Tribol Lett. 2001; 9(3-4):181-185.
21 Jones WR, Jansen MJ. Tribology for space applications. Proc Inst Mech Eng Part J J Eng Tribol. 2008; 222(8):997-1004.
22 Wilkens W. Contamination danger by oil-lubricated ball bearings in spacecraft. J Spacecraft Rockets. 1971; 8(9):962-965.
23 Fote AA, Slade RA, Feuerstein S. The prevention of lubricant migration in spacecraft. Wear. 1978; 51(1):67-75.
24 Bruzzone AAG, Costa HL, Lonardo PM, Lucca DA. Advances in engineered surfaces for functional performance. CIRP Ann-Manuf Techn. 2008;57(2):750-769.
25 Liao SJ, Huang W, Wang XL. Micro-Magnetic Field Arrayed Surface for Ferrofluids Lubrication. J Tribol. 2012; 134(1):021701-021707.
26 Huang W, Wang XL. Biomimetic design of elastomer surface pattern for friction control under wet conditions. Bioinspiration Biomimetics 2013;8(4):46001-46006.
27 Yu HW, Huang W, Wang XL. Dimple patterns design for different circumstances. Lubr Sci. 2013; 25(2):67-78.
28 Yan DS, Qu NS, Li HS, Wang XL. Significance of dimple parameters on the friction of sliding surfaces investigated by orthogonal experiments. Tribol Trans. 2010; 53(5):703-712.
29 Yuan SH, Huang W, Wang XL. Orientation effects of micro-grooves on sliding surfaces. Tribol Int. 2011; 44(9):1047-1054.
30 Petrov JG, Ralston J, Schneemilch M, Hayes RA. Dynamics of partial wetting and dewetting of an amorphous fluoropolymer by pure liquids. Langmuir. 2003; 19(7):2795-2781.
31 Ramiasa M, Ralston J, Fetzer R, Sedev R. The influence of topography on dynamic wetting. Adv Colloid Interface Sci. 2014; 206:275-293.
32 Young T. An essay on the cohesion of fluids. Phil Trans R Soc Lond. 1805; 95:65-87.