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Micro-grooves design to modify the thermo-capillary migration of paraffin oil

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Abstract Thermo-capillary migration is a phenomenon in which thermal gradients drive a liquid to flow without any external force. It is important to prevent the migration of liquid lubricants for moving mechanisms. This study aimed to investigate the influence of micro-grooves patterns on the migration of paraffin oil and obtain a design concept of micro-grooves patterns to obstruct the migration. Micro-grooves patterns with different orientations and geometric parameters were fabricated on the surface of SUS 316 stainless steel. Migration experiments of paraffin oils on each specimen were performed under various temperature gradients. The results indicated that micro-grooves patterns strongly modified the thermo-capillary migration. Micro-grooves perpendicular to the temperature gradient obstructed the migration effectively, while micro-grooves parallel to the temperature gradient accelerated the migration. The width and depth of micro-grooves influenced the migration behavior obviously, and the effects of these geometric parameters were discussed in detail.

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1 Introduction

The Marangoni effect, also visually known as "tears of wine", was named after Italian physicist C. Marangoni. It describes a phenomenon that substantial variations in surface tension will cause the motion of a fluid without any external force [1]. Thermal gradient is one of the inducements that can generate the variations of surface tension of a liquid, which causes the liquid to move from a high temperature region to a low-temperature region. The thermal gradient induced movement of a liquid is referred to as thermo-capillary migration.

The thermo-capillary migration plays a fascinating role in many industrial applications, such as hard disk, inkjet printing, microfluidics, and micro-electronics [2]. For space lubrication, where the temperature changes from −100 to 200 °C, the migration of liquid lubricants strongly affects the device performance and service life [3–5]. Moreover, frictional heat generated at the contacting asperities on the surfaces of moving element can create a temperature gradient between the contact area and surroundings, which induces the migration of liquid lubricants from rubbing area to a relatively low-temperature area [6–8]. Therefore, it is necessary to prevent the migration to guarantee proper lubrication for moving mechanisms in the space.

The migration of a liquid has been experimentally and theoretically researched for centuries. Differences in composition and concentration or the temperature within a liquid would induce the migration. Moreover, there exist other mechanisms impelling the migration. The radius of curvature for a micro-rough surface can cause a variation in the surface tension and drive the liquid to spread across the surface akin to capillary action [9]. Klien et al. [10] experimented on the migration of oil drops on both ground and polished surfaces and found that the surface topography strongly influenced the oil migration. Our previous research demonstrated that the orientation of grinding scars also changed the migration behavior effectively [11].

The design of the surface is often of the utmost importance for the correct functioning of the part since the most physical phenomena involving exchange of energy and/or signal transmission take place on surfaces [12]. Over the last decade, more attentions have been paid to the structured or textured surfaces [13–16]. Distinguished to the traditional surface finishing, textured surfaces are the surfaces with fine scale, high aspect ratio, and periodic structures, which offer designers additional freedom to create novel functions or combinations of functions [17].

Currently, surface texture is widely used for tribological purposes. It can help preserve lubricant, trap wear debris to decrease further wear, and, particularly, provide additional hydrodynamic effects to increase the load carrying capacity of parallel sliding surfaces [18–20]. What effect does the surface texture have on the thermo-capillary migration of the lubricant? Will the arrayed surface structures accelerate or obstruct the migration? Further research is necessary.

Therefore, this paper is organized as follows: First, the micro-grooves patterns are fabricated on the surface of SUS 316 stainless steel. Then, the effects of micro-grooves on the thermo-capillary migration behavior under various temperature gradients are studied. Special attentions are paid to the influence of geometric parameters and orientation of micro-grooves. A design principle of micro-grooves is proposed for modifying the behavior of thermo-capillary migration.

2 Experimental

2.1 Apparatus

Figure 1 shows the schematic diagram of the apparatus used in this study. The metal specimen was tightly attached to the heating and cooling blocks to obtain a good thermal contact. By simultaneously controlling the heating and cooling blocks, a temperature gradient could be generated along the length direction of the metal specimen. A thermal imaging acquisition device (Fluke, USA) and thermocouples were used to obtain the real-time temperature distribution on the specimen surface. The measurement by the thermal imaging acquisition device shows that the temperature decreased nearly linearly along the length of the specimen, and the average temperature gradient was used in this study. A digital video camera was employed to monitor the dynamic migration process. Key frames from the video were extracted to calculate the migration velocity via the image and video editing software.

2.2 Specimen fabrication

Migration experiments were performed on metal specimens with the dimensions of 76 mm × 30 mm × 3 mm. All specimens were made of SUS 316 stainless steel. The test surface was manufactured by grinding and polishing sequentially to obtain a final surface roughness, Ra, in the range of 10-20 nm together with a high degree of flatness. Then, the micro-grooves patterns were fabricated on the surface via photolithography combined with an electrolytic etching process as mentioned in refs [21, 22]. These processes could precisely control

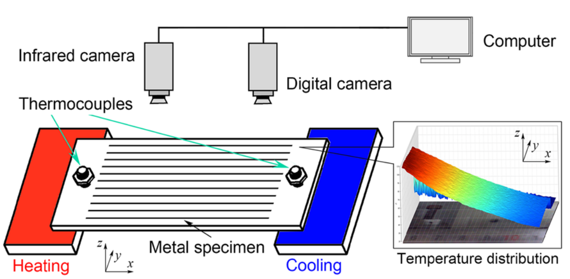

Fig. 1 Schematic diagram of the experimental apparatus

the dimensions and orientations of micro-grooves without any undesired effect on the surface. The surface roughness and geometric dimensions described in this article were measured by a surface mapping microscope (Rtec instruments, USA). Table 1 lists the geometric parameters for the patterns studied in this research.

Figure 2a shows a typical surface topography for the micro-grooves of 200 μm in width and 22 μm in depth along the length of the specimen, and Fig. 2b shows the surface with micro-grooves of 100 μm in width and 60 μm in depth perpendicular to the length of the specimen. The area density *r* was defined as the ratio of the grooves area over the whole textured area. As illustrated in Fig. 2, this value can be calculated as *w/l*.

2.3 Test procedure

To rule out any effects of additives, paraffin oils with different kinematic viscosities were used for all experiments. The kinematic viscosities were obtained under a constant temperature of 40 °C. The main physical parameters of paraffin oil with kinematic viscosity $v = 5.7\ mm^2/s$ are listed in Table 2.

Before experiments, each specimen was ultrasonically cleaned in acetone and ethanol, rinsed with deionized water, and finally blow-dried with nitrogen, sequentially. A microliter syringe was used to precisely control the quantity of paraffin oil. In addition, a scale plate was fixed near the specimen to ensure that the paraffin oil droplets were always placed at the same location. The main test conditions are listed in Table 3.

3 Results

Figure 3 shows the dynamics migration process of a droplet with the viscosity of 5.7 mm^2/s on the untextured surface under a temperature gradient of 2.2 °C/mm. The migration distance was measured at the front edge of the droplet and plotted as a function of time. Initially, the migration distance increased very fast, meaning that the migration velocity was fast at beginning. As time elapsed, the migration velocity decreased and finally diminished close to zero. So, to simplify the comparison of the migration behavior, in the following figures, the migration distance of 20 mm was chosen as a reference and the mean migration velocity within this distance was calculated.

Figure 4 presents the effects of the orientation of micro-grooves on the migration velocity. The surfaces with micro-grooves parallel or perpendicular to the temperature gradient, were tested and compared to untextured surface. The dimensions of the micro-grooves are 100 μm in width, 22 μm in depth, and area density is 10 %. The paraffin oils with viscosities of 5.7, 13.4 and 26.9 mm^2/s were used in the tests. As shown in Fig. 4a, under a temperature gradient of 3.0 °C/mm and the viscosity of 5.7 mm^2/s, the migration velocity on surface with parallel grooves is approximately 7.17 mm/s, which is quadruple higher than the 1.54 mm/s, observed for the untextured surface, and the surface with perpendicular grooves exhibited a slow velocity, just about 0.8 mm/s. Figure 4b and 4c present the migration velocities with viscosities of 13.4 and 26.9 mm^2/s. It can be found that on each surface, the migration velocity

Table 1 Geometric parameters for the patterns of micro-grooves

Specimen no.	*Width w* (μm)	Depth *h* (μm)	Pitch *l* (μm)	Area density *r* (%)	Orientation
1	0	0	0	0	Untextured
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

Fig. 2 Photographic and 3D topographic images of the specimen surfaces: **a** micro-grooves (200 μm in width, 22 μm in depth) parallel to the specimen length, and **b** micro-grooves perpendicular to the specimen length (100 μm in width, 60 μm in depth)

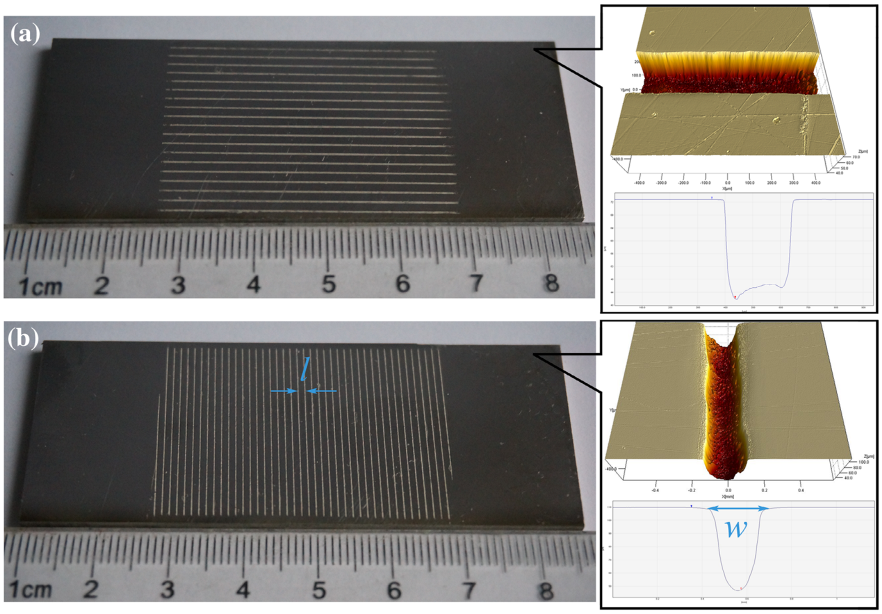

Table 2 Physical parameters of paraffin oil

Parameter	Value
Kinematic viscosity, ν	5.7 mm^2/s
Liquid density, ρ	0.82394 g/cm^3
Surface tension, σ	25.8 mN/m
Surface-tension coefficient, σ_T	0.085 mN/(m °C)
Thermal diffusivity, κ	1.564 mm^2/s

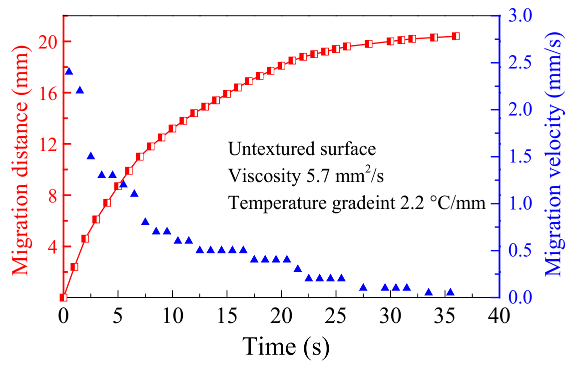

Fig. 3 Migration distance of paraffin oil with viscosity of 5.7 mm^2/s versus elapsed time, under a temperature gradient of 2.2 °C/mm

Table 3 Experimental conditions

Environmental temperature	20 °C
Experimental lubricant	Paraffin oil
Temperature gradient	0.6–3 °C/mm
Kinematic viscosity (at 40 °C)	5.7–53.6 mm^2/s
Oil volume	5 μL

decreases with increasing viscosities. While compared the velocities on these three surfaces, a similar trend could be found: parallel grooved surface achieves the faster velocity and perpendicular grooved surface obtains the slower. In other words, micro-grooves perpendicular to the temperature gradient will obstruct the thermo-capillary migration, while parallel ones will accelerate it.

Figure 5 shows the effects of groove depth on the migration velocity for the grooves parallel to the temperature gradient. The paraffin oil with viscosities of 5.7, 13.4, 26.9 and 53.6 mm^2/s were used and the tests were conducted under the temperature gradients of 2.2 and 3.0 °C/mm. As shown in Fig. 5a, for the oil viscosity of 5.7 mm^2/s under a temperature gradient of 2.2 °C/mm, the micro-grooves with a depth of 22 μm yields a velocity about 1.22 mm/s, which is nearly twice the 0.64 mm/s observed for the untextured surface; when the depth increased to 60 μm, the migration velocity is increased to 2.0 mm/s, which is

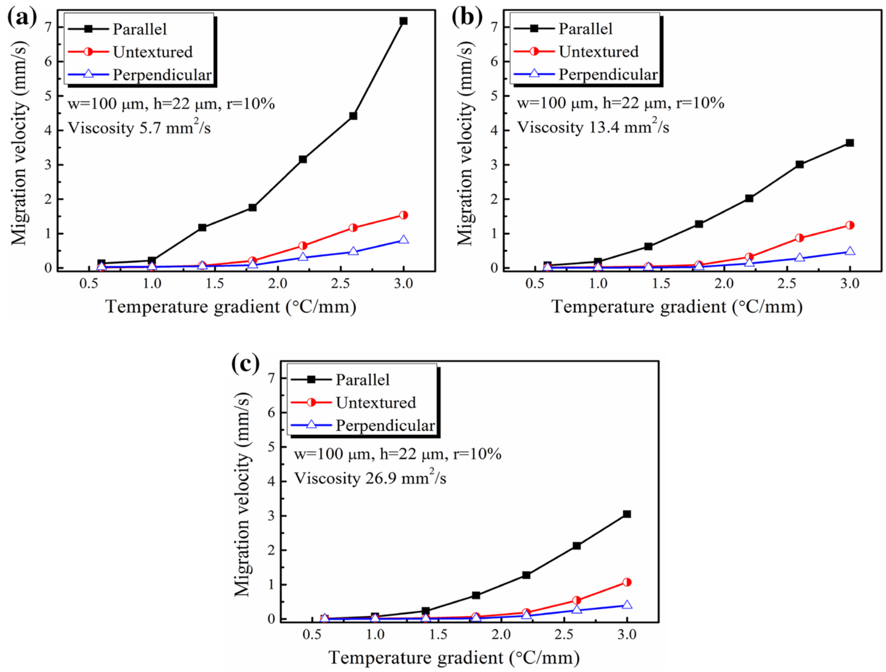

Fig. 4 The effects of the orientation of micro-grooves on the migration velocity, under different temperature gradients with different kinematic viscosities **a** 5.7 mm^2/s, **b** 13.4 mm^2/s and **c** 26.9 mm^2/s

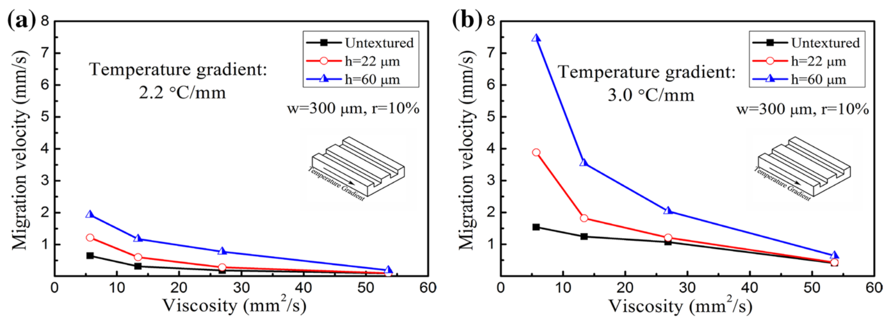

Fig. 5 The effects of groove depth on the migration velocity for the grooves parallel to the temperature gradient, under the different temperature gradients of **a** 2.2 °C/mm and **b** 3.0 °C/mm

nearly triple that on untextured surface. A similar effect of depth is observed when the temperature gradient increased to 3.0 °C/mm, as shown in Fig. 5b. It means that on surface with grooves parallel to the temperature gradient, the migration velocity is accelerated with increasing depth, particularly, at high temperature gradient.

The influence of groove depth on the migration velocity for the grooves perpendicular to the temperature gradient is shown in Fig. 6. The area density *r* was kept constant ($r = 10$ %). As shown in Fig. 6, a temperature gradient of 2.2 °C/mm with a paraffin oil viscosity of 5.7 mm^2/s yields a migration velocity on the untextured surface for approximately 0.65 mm/s, which is much higher than for the texture surface. The velocity for 60 μm deep micro-grooves is the lowest. Obviously, the migration velocity trends for the two temperature gradients are similar, all decrease with increasing depth. Therefore, for perpendicular grooves, increasing the depth impedes the thermocapillary migration.

The width is another important geometric parameter of micro-grooves. The effects of groove width on the migration behavior for the grooves parallel to the temperature gradient are shown in Fig. 7. Specimens with micro-grooves of 100, 200, and 300 μm in width were tested. The area density r was kept constant as r = 10 %. With the oil viscosity of 5.7 mm^2/s, the 100 μm grooves exhibited the fastest migration velocity, approximately 7.17 mm/s shown

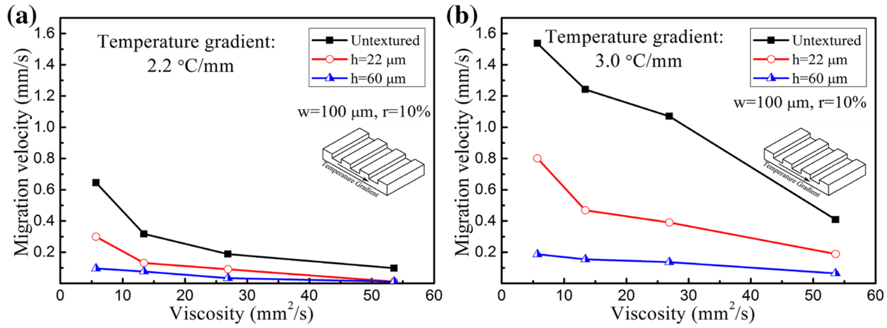

Fig. 6 The effects of groove depth on the migration velocity for the grooves perpendicular to the temperature gradient, under different temperature gradients of **a** 2.2 °C/mm and **b** 3.0 °C/mm

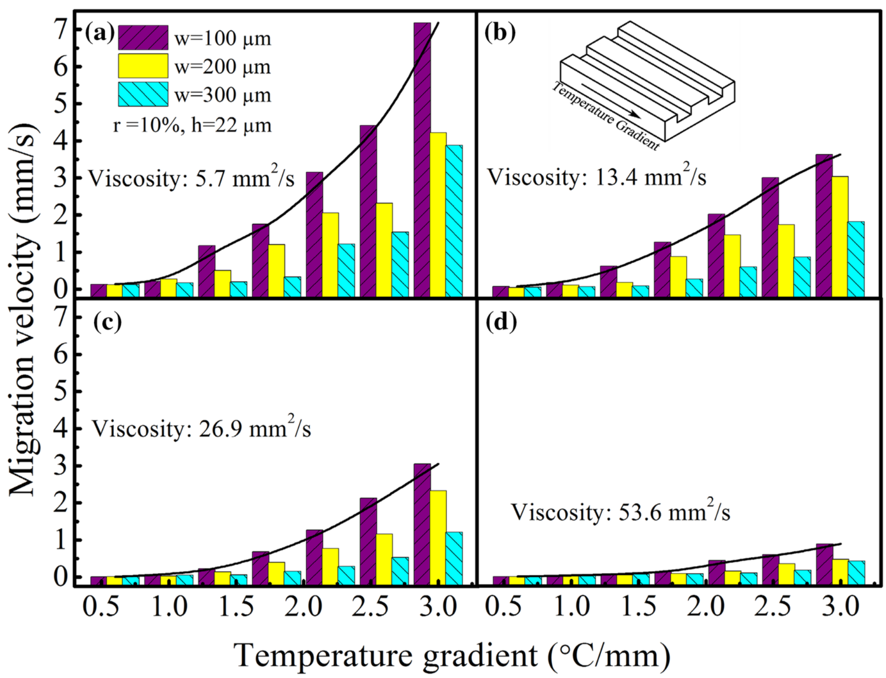

Fig. 7 The effects of groove width on the migration velocity for the grooves parallel to the temperature gradient, under increasing temperature gradients with different kinematic viscosities of **a** 5.7 mm^2/s, **b** 13.4 mm^2/s, **c** 26.9 mm^2/s and **d** 53.6 mm^2/s

in Fig. 7a, and the migration velocity dropped with increasing width. Meanwhile, it can be seen that the migration velocity exhibits significant nonlinearity under high temperature gradients. For paraffin oil with different viscosities, as shown in Fig. 7b–d, the migration velocity trends of these specimens are similar: all rates decreased with increasing width.

Figure 8 shows the effects of groove width on the migration behavior for the grooves perpendicular to the temperature gradient. The dimensions were the same as that in Fig. 7. It can be seen that migration velocity is increased with increasing temperature gradient. For these three specimens with different widths, only a small difference existed between the migration velocities under the same temperature gradient. Thus, for the perpendicular grooves, the width has little effect on the migration.

Figure 9 shows the detailed migration process of the paraffin oil ($\nu = 5.7$ mm^2/s) on the untextured surface, surface with the grooves parallel or perpendicular to the temperature gradient of 3.0 °C/mm, respectively. Each of them is a merged image composed of 14 video frames. As shown in Fig. 9a, when a droplet was placed on the untextured surface, the migration occurred from the warm region to the cold region, i.e., along the length direction of the specimen, accompanied with diffusion in the width direction of the specimen. With time elapsed, an interesting phenomenon emerged that the paraffin oil contracted back to the droplet shape as the liquid continually

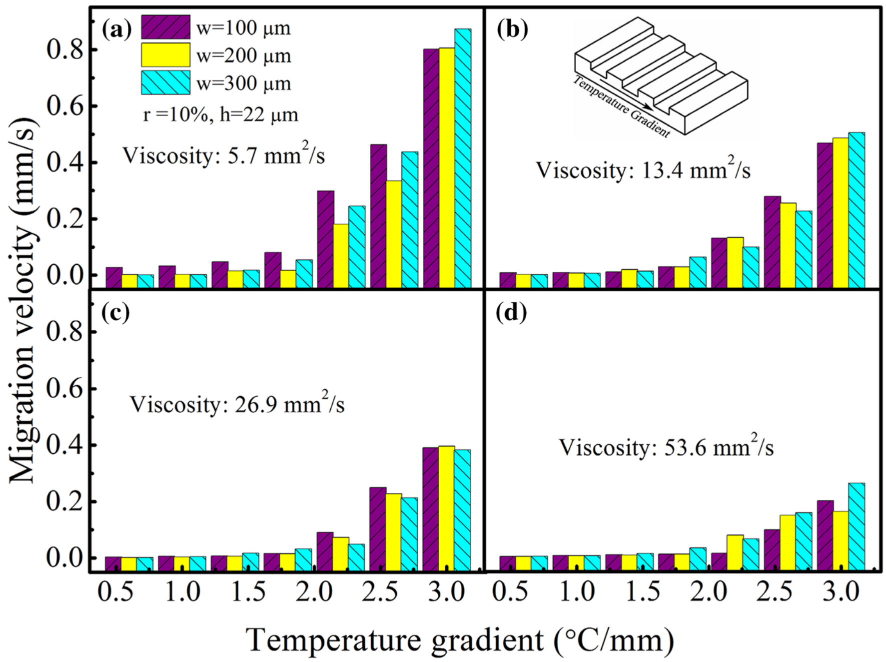

Fig. 8 The effect of groove width on the migration velocity for the grooves perpendicular to the temperature gradient, under increasing temperature gradients with different kinematic viscosities of **a** 5.7 mm^2/s, **b** 13.4 mm^2/s, **c** 26.9 mm^2/s and **d** 53.6 mm^2/s

migrate to cold region. As shown in Fig. 9b, on the surface with micro-grooves parallel to the temperature gradient, the diffusion and contraction phenomena were also observed. Meanwhile, it is clearly to see that the diffusion level was lower than that on the untextured surface. However, on surface with perpendicular micro-grooves, as shown in Fig. 9c, the droplet was obstructed by the grooves and didn't contracted back to the droplet shape.

It is known that an oil droplet will diffuse to the surround on a heated surface. So, as the droplet placed on a surface, the migration occurs accompanying with the diffusion phenomenon in the width direction. Since the temperature of the droplet decreases along with the migration process, the viscosity and liquid–gas interfacial tension of the droplet would increase. Consequently, the liquid will contract to the shape of a droplet during the migration process. For surfaces with micro-grooves patterns parallel to the temperature gradient, the patterns impede the diffusion and promote the migration, resulting in a faster migration velocity. However, for surfaces with micro-grooves patterns perpendicular to the temperature gradient, the patterns promote diffusion and impede migration.

4 Discussion

Young's equation defines the force balance between the tension existing at a solid–liquid (γ_{SL}), solid–gas (γ_{SG}), liquid–gas (γ_{LG}) interface and the contact angle (θ). In this study, when a droplet is placed to a level specimen with a temperature gradient, the interfacial tension gradient at the solid–liquid surface is generated, i.e., the solid–liquid interfacial tension at the front of the droplet is greater than that at the rear surface. This imbalanced force results in a traction vector that causes the droplet to migrate from a warm region toward a colder region. Meanwhile, at the molecular view, there exists a phenomenon that molecules will drift along the temperature gradient, which is widely known as the Soret effect, also called thermophoresis [23, 24]. There might be some internal relation between the migration and the thermophoresis.

Figure 10 shows a diagram of the oil migrating to a groove perpendicular to the temperature gradient. It is known that the pressure inside a droplet is related to the curvature and the liquid–gas interfacial tension of the liquid, which can be expressed by the Young–Laplace equation [25]. When considering the influence of the interfacial curvature of the droplet on the

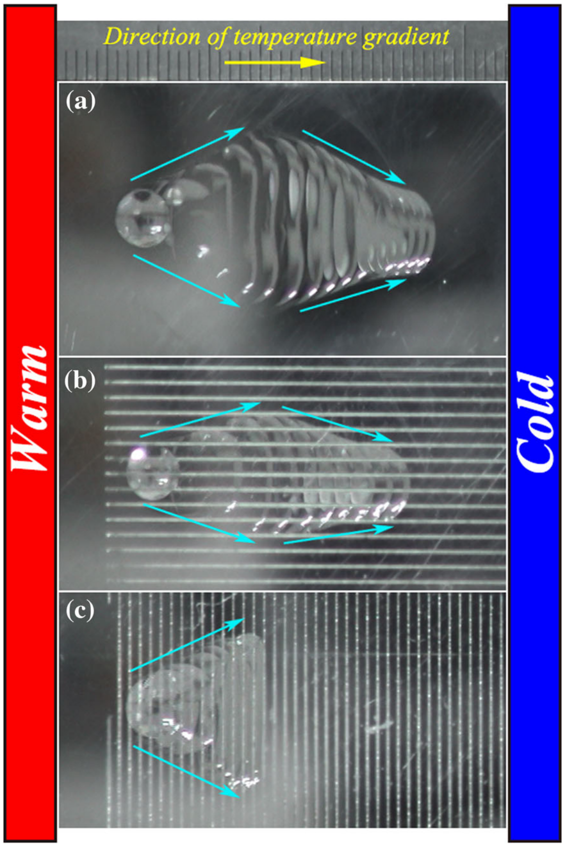

Fig. 9 The detailed thermo-capillary migration process on different surfaces under a temperature gradient of 3.0 °C/mm: **a** untextured surface, **b** surface with parallel grooves and **c** surface with perpendicular grooves

inner pressure, the pressure gradient in the droplet can be obtained as [26]:

$$\frac{dP}{dx} = -\frac{\gamma}{R^2}\frac{dR}{dx} \tag{1}$$

where P is the inner pressure of the drop, R is the interfacial radius of curvature for the drop, and γ is the tension at liquid–gas interfacial of the droplet.

As shown in Fig. 10, when the paraffin oil approaches to the edge of a groove, the liquid gathers at the edge, which makes the curvature of the advancing meniscus less than that of the receding meniscus (from stage I to II). As indicated by Eq. 1, a Laplace pressure difference between the advancing and receding boundaries of the droplet is produced, yielding a hydrodynamic force in the droplet that resists the migration process. If the migration driving force is larger than the resistance, the droplet migrates into the groove, while the hydrodynamic force still works on the droplet (stage III). And the force will last until the groove is full filled. Therefore, the existence of micro-grooves perpendicular to the temperature gradient obstructs the migration, and deep grooves will actually increase the time duration of the hydrodynamic force, which eventually induces a more significant obstruction effect than the shallower ones. Besides that, existence of perpendicular grooves will bring in more free-energy barriers needed to be overcome [27, 28].

Figure 11 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 liquid–vapor interfacial tension γ_{LG} component in the horizontal direction [29]. Furthermore, the micro-grooves can act as micro-capillaries parallel to the temperature gradient, producing an extra force, $F_{capillary}$, which increases the migration velocity in the temperature gradient direction. The narrower the micro-grooves

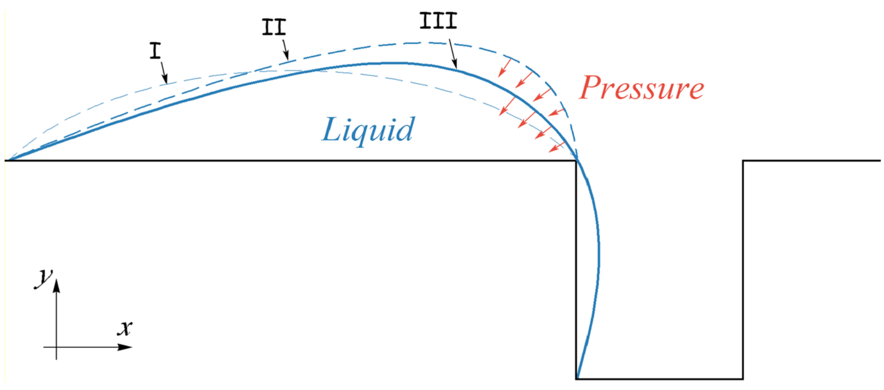

Fig. 10 Diagram for a liquid migrating to a groove perpendicular to the temperature gradient

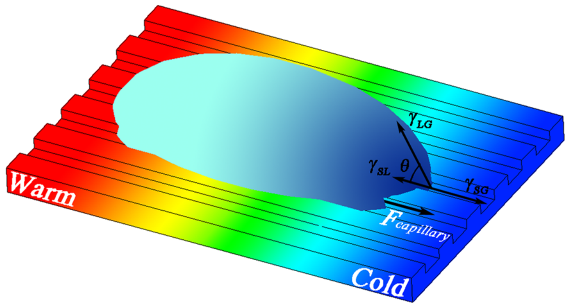

Fig. 11 Interfacial tensions at the three-phase contact line of a sessile droplet on a surface with micro-grooves parallel to the temperature gradient

are, the more significant the capillarity effect will be. In other words, this extra force, $F_{capillary}$, increased with increasing depth or decreasing width, therefore, the migration velocity will be increased.

In all experiments, the migration, occurs from warm to cold regions. The onset behavior of migration is determined by two time scales: thermo-capillary time scale and diffusive time scale. Temperature gradients on a liquid film will change the surface tension of the fluid and make it disequilibrium. The induced thermos-capillary forces will pull the liquid from warmer to cooler regions until equilibrium reaches [30]. The thermo-capillary time scale is defined as:

$$t_{therm}^2 = \frac{\rho d^3}{\sigma_T \Delta T} \tag{2}$$

and the diffusive time scale is defined as:

$$t_{diff}^2 = \frac{d^4}{\nu\kappa} \tag{3}$$

where d is the mean droplet depth, ΔT is a characteristic temperature difference across the droplet layer, ν is the kinematic viscosity, ρ is the liquid density, σ is the surface tension, σ_T is the surface-tension coefficient, κ is the thermal diffusivity [31]. With these two time scales, the Marangoni number can be calculated as:

$$M_a = \frac{t_{diff}^2}{t_{therm}^2} = \frac{\sigma_T \Delta T d}{\rho\nu\kappa} \tag{4}$$

The Marangoni number determines the stability of this migration. The migration velocity of the drop will be increased with increasing Marangoni number [32].

In this study, the volume (V) of droplet is constant. As the droplet placed on the specimen surface, it migrated from warm to cold area forming a thin film. For being convenient to the analysis, it is regarded as a uniform thin film and key frames during the migration process were extracted to measure the area (A) of the film, the mean droplet depth (d) can be calculated as V/A. We calculated the Marangoni number for the paraffin oil ($\nu = 5.7$ mm^2/s) on untextured surface and surfaces with different geometric parameters, i.e., surfaces with grooves parallel to the temperature gradient ($w = 100$ μm, $h = 22$ μm and $w = 300$ μm, $h = 60$ μm), and surface with grooves perpendicular to the temperature gradient ($w = 100$ μm, $h = 22$ μm, $w = 100$ μm, $h = 60$ μm, and $w = 200$ μm, $h = 22$ μm). The migration velocities versus the Marangoni numbers on these surfaces are shown in Fig. 12.

It can be seen that for all the surfaces, the migration velocities increase with the increasing of Marangoni number. Obviously, the patterns of micro-grooves have a strong influence on the migration velocity, different migration velocities are exhibited under the same value of Marangoni number. For surface with parallel grooves, the migration velocity is higher than that of untextured surface, and for perpendicular ones, the velocity is lower than that of untextured surface. It means that existence of micro-grooves will modify the liquid migration behavior on the surfaces. Surface design of micro-grooves perpendicular to the

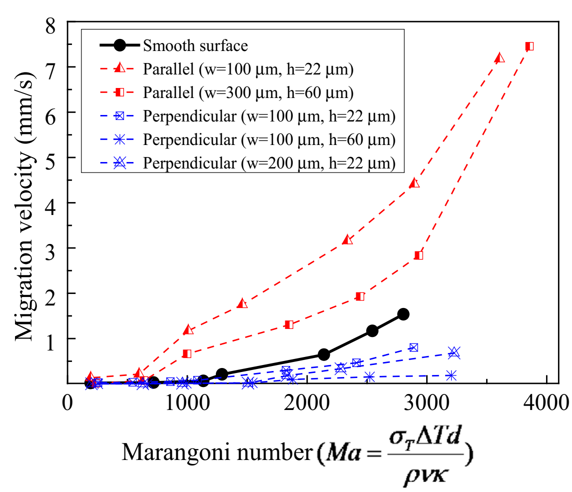

Fig. 12 The migration velocities of paraffin oil versus the Marangoni number on the surfaces with micro-grooves of different geometric parameters

temperature gradient can significantly obstruct the migration. The depth of micro-grooves is an effective parameter, deeper grooves ensure better obstruction to the liquid migration. In addition, in the real application, the micro-grooves design could be straight or curved, deep or shallow, and wide or narrow, which provide more freedom to obtain preferable behavior.

5 Conclusions

In this study, experiments were performed to investigate the effects of orientation and geometric parameters of micro-grooves on the thermos-capillary migration of paraffin oil. The following conclusions were drawn from this study:

1. The pattern of micro-grooves has a strong effect on the fluid migration behavior induced by temperature gradient.
2. The groove orientation on the surface plays an important role in the migration behavior. Micro-grooves perpendicular to the temperature gradient effectively obstructs the migration. Increasing the groove depth could obtain better obstruction to the thermo-capillary migration. The width has little effect on the migration behavior.
3. For micro-grooves parallel to the temperature gradient, increasing the depth or decreasing the groove width enhances the thermo-capillary migration. Narrower grooves achieve faster migration velocity.

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