A Surface Texture Design to Obstruct the Liquid Migration Induced by Omnidirectional Thermal Gradients

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ABSTRACT: Thermo-capillary migration is a phenomenon in which surface thermal gradients drive a liquid to flow from warm to cold regions without external forces. It is important to prevent the migration of liquid lubricants on rubbing surfaces. In this paper, a pattern of microdimples was proposed to obstruct the liquid migration induced by an omnidirectional thermal gradient. Microdimple patterns were fabricated on the surfaces of SUS316 stainless steel. Experiments were performed to investigate the influence of microdimple patterns with different geometric parameters on the migration behavior of paraffin oil. In particular, this study focused on the interfacial flowing near the microdimples. The results demonstrated that microdimples have a significant obstructive effect on migration, whereas dimples have a retaining effect, and the adjacent dimples have an interacting effect.

1. INTRODUCTION

Because most important physical events involving energy exchange and/or signal transmission take place on surfaces,1−3 investigations on surface phenomena, in particular, wetting and spreading movements, have revealed a wide range of processes in both natural and industrial settings.4−8

Surface-tension-driven migration occurs when substantial variations in surface tension cause the motion of a fluid without external forces. Differences in composition and concentration or the temperature within a liquid, as well as the presence of surfaces with microstructures, can all induce a spatial surface tension gradient. A thermal gradient is a very common occurrence that can cause a liquid to move from a high-temperature region to a low-temperature region. Thermal gradient-induced movement of a liquid is referred to as thermal capillary migration.13−16

Thermal capillary migration is of central importance to a number of industrially manufactured products such as miniature ball bearings, hard disks, inkjet printers, microelectronics, etc.17−20 For instance, the heat generated by friction can create a thermal gradient that drives a lubricant to flow from a high-temperature locale to an area of relatively low temperature, resulting in the loss of lubricant from the contact area.21−23 In a space environment, one of the most prominent features is the extremely large temperature range (−100−200 °C), with thermal gradients that change direction or are omnidirectional, which induce the migration of liquid lubricants on the surfaces of mechanical components.24 This type of movement would seriously affect the intended behavior of the lubrication and could cause potential failure of moving parts, particularly for the cases where the amount of lubricant is limited.

Surface energy and topography, as well as viscosity, all have a strong influence on liquid action. Experimental and theoretical studies have addressed the obstruction of liquid migration for many years.25−29 Clearly, liquid lubricants with low surface tensions or viscosities are prone to migrate. Thus, liquid lubricants with high surface tensions and viscosities are usually employed in space to prevent thermal capillary migration.30 Roberts et al.31,32 modified rubbing surfaces by placing low-surface-energy fluorocarbon compounds around the contact region. This generated chemical gradients on the surface and effectively confined lubricant films to the desired location.

Over the past decade, surfaces have been structured, textured, or engineered to provide specific functions for several industrial applications.33−36 The radius of curvature for a microrough surface varies with depth and can cause differences in surface tension, which changes the spreading movement of a liquid on the surface.37,38 Lei and his co-workers fabricated anisotropic microgrooved organogel surfaces, which act as barriers to restrict water droplets from sliding perpendicular to the grooves’ direction. Our previous research39,40 showed that surface roughness and orientation strongly influences the migration behavior of paraffin droplets. Detailed investigations on the effects of microgrooved patterns revealed that microgrooves that are perpendicular to the temperature gradient effectively obstruct this thermally driven migration of liquids. However, when the features are parallel to the temperature gradient, movement is accelerated. Therefore, microgrooves could only be an effective way to obstruct

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thermally driven migration for a fixed direction of a temperature gradient.

Considering the complicated working conditions in aerospace (e.g., limited lubricant and steep omnidirectional thermal gradients), it is important to prevent the migration of liquid lubricants driven by directionally unstable thermal gradients. Hence, is there a surface structure that can inherently mitigate or obstruct this movement and guarantee the lifetime of a lubricant?

Herein, patterns of microdimples were employed to restrict or prevent unwanted liquid flow under omnidirectional thermal gradients, and the influence of different geometric parameters on thermo-capillary driven migration was studied. Particular attention is paid to the flowing interface near the dimple and the effects of the neighboring dimples when the liquid moves over them.

2. EXPERIMENTAL SECTION

2.1. Experimental Apparatus. Two experimental apparatuses were designed for this study, as shown in Figure 1. First, to verify the obstructing effects of the patterns of microdimples, an experimental apparatus was designed as shown in Figure 1a. The circular substrate was firmly secured to the rod and the ring to ensure good thermal contact. The rod was heated to the desired temperature via an embedded ceramic plate heater, while the ring was immersed in ice water to maintain a constant temperature of 0 °C. Thus, the omnidirectional thermal gradients were generated on the surface of the specimen, i.e., from the center to the edge. Then, an apparatus was designed to determine the effects of the geometric parameters of microdimple patterns on migration behavior, as shown in Figure 1b. The rectangular specimen could be heated on the left side and cooled on the right side to achieve a unidirectional thermal gradient, i.e., from the left to the right of the specimen. The thermography, obtained by an infrared camera, confirmed the omnidirectional and unidirectional thermal gradients.

2.2. Specimen Preparation. All specimens were made of SUS 316 stainless steel. The testing surface was sanded and polished to obtain a flat surface with a final surface roughness, Ra, ranging from...
10–20 nm. Then, the pattern of microdimples was fabricated in the middle of the testing surface by photolithography and electrolytic etching, as described in the literature.42,43 These techniques precisely manufactured the dimple geometry and distribution of features without the need for further surface abrasion. The surface roughness and shape of the dimples was characterized using a white-light interferometer from Rtec-instruments (California, USA). Figure 2 presents a typical surface topography for microdimples that are 300 μm in diameter \( d \), 50 μm in depth \( h \) and 10% in area density \( r \). The intervals between dimples were changed to obtain a series of different area densities \( r \). As illustrated in Figure 2a, the area density can be calculated as follows:

\[
\rho = \frac{\pi d^2}{4h} \tag{1}
\]

2.3. Testing Method. Prior to the experiments, each specimen was ultrasonically cleaned in acetone and alcohol, rinsed with deionized water, and dried with nitrogen. To rule out the effects of additives on oil migration, paraffin oils, with different kinematic viscosities, were obtained from crude oil fractionation and used for all experiments. The values of kinematic viscosity were obtained under a constant temperature of 40 °C with an Ubbelohde viscometer, which is a capillary-based measuring instrument.

The macroscopic migration process of a droplet was recorded by a digital video camera. The key frames of the video were then extracted to calculate the velocity of migration using image and video editing software. The microscopic spreading process at the front edge of the paraffin droplet was observed using a digital microscope, Keyence VHX-600 (Osaka, Japan). An infrared camera from Fluke (WA, USA) and thermocouples were used to obtain the real-time temperature distribution on the surface of the specimen, and then to calculate the thermal gradients. For all experiments, 5 μL of paraffin oil was placed on the substrate surface using a microliter syringe. The main test conditions are listed in Table 1.

Table 1. Experimental Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment temperature</td>
<td>19–21 °C</td>
</tr>
<tr>
<td>Experimental liquid</td>
<td>Paraffin oil</td>
</tr>
<tr>
<td>Thermal gradient</td>
<td>2–3 °C/mm</td>
</tr>
<tr>
<td>Kinematic viscosity (at 40 °C)</td>
<td>5.7–53.6 mm²/s</td>
</tr>
<tr>
<td>Volume of oil</td>
<td>5 μL</td>
</tr>
</tbody>
</table>

3. RESULTS

3.1. The Migration Process under Omnidirectional Thermal Gradients. First, circular specimens were employed to investigate the effect of microdimples on the omnidirectional thermal gradient migration. The dimensions of the specimen were 76 mm in diameter and 3 mm in thickness. The center area was textured with a pattern of microdimples 300 μm in diameter, 15 μm in depth, and 10% in area density. Paraffin oil with a kinematic viscosity of 5.7 mm²/s (at 40 °C) was dropped on the central region of the specimen (see Figure 2). As migration proceeded, the paraffin oil flowed under action of the omnidirectional thermal gradient until reaching the textured surface. Instead of continuing to spread out, the majority of the oil was instead confined to the central region of the specimen (see Figure 4). Therefore, the droplet stops almost completely on the textured surface and is unable to migrate further.

Table 3 presents a quantitative comparison of the migration of a paraffin droplet on the smooth and textured surfaces. In this figure, the spreading diameter of the paraffin oil was measured and plotted as a function of time. Initially, the same volume of paraffin oil was dropped onto the center of both specimens, and the diameter of the droplet was nearly the same at approximately 0.7 mm. As time elapsed, the migration of the droplet on the smooth surface increased faster than on the textured surface, and after 19 s, its diameter was nearly 200% larger; this can be clearly observed by comparing panels a4 and b4 of Figure 3. At this point, the diameter of both droplets increased quite slowly and was nearly invariable.

3.2. The Effect of Dimple Depth. To simplify the investigation to the effects of geometric patterns on droplet migration behavior, the migration experiments in the following sections were conducted using unidirectional thermal gradients, e.g., via the experimental apparatus shown in Figure 1b. Paraffin

![Figure 3. Details of the migration process induced by omnidirectional thermal gradients on (a) a smooth surface and (b) a surface with a pattern of microdimples.](image-url)
oil was dropped at the starting position on the warm side, and its movement was recorded and analyzed over a distance of 20 mm to evaluate the migration velocity (based on the location of the droplet’s front edge in successive images).

Figure 5 presents the influence of the dimple depth on droplet migration. Smooth and textured specimens with dimples depths of 15 or 50 μm, a constant diameter of 300 μm, and an area density of 10% were tested using paraffin oils with viscosities of 5.7, 9.0, 13.4, 19.1, 26.9, and 53.6 mm²/s. The migration velocities under a thermal gradient of 2.2 °C/mm are shown in Figure 5a. It is of note that for each specimen, the migration velocity decreased with increasing kinematic viscosities. The specimen with microdimples of 15 μm in depth yielded a slightly lower migration velocity when compared with the smooth specimen. At a microdimple depth of 50 μm, the migration velocity decreased to nearly zero, which means that the migration velocity decreased with an increase in the depth of the features. Figure 5b presents the migration velocity under a thermal gradient of 3.0 °C/mm. A steeper thermal gradient clearly increased the migration velocity. Therefore, as indicated by the similar trend in dimple depth and migration rate under these two thermal gradients, migration velocities decreased with increasing depth, with the smooth surface representing a depth of zero.

3.3. The Effect of Dimple Density. The area density is another important geometric parameter of the microdimple pattern, and its effect on migration behavior is shown in Figure 6; specimens with a dimple area density of 10% or 20%, a diameter of 300 μm, and a depth of 15 μm were tested. Figure 6a shows the migration velocities for different area densities under a thermal gradient of 2.2 °C/mm. A rapid increase in the area density led to decreased migration velocity, and a similar effect was noted with increasing kinematic viscosities. A thermal gradient of 3.0 °C/mm yielded a higher migration velocity than that obtained under a thermal gradient of 2.2 °C/mm, as shown in Figure 6b. At a kinematic viscosity of 5.7 mm²/s, the migration velocity on the smooth surface was approximately 1.54 mm/s, which was nearly 200% higher than the 0.73 mm/s observed for an area density of 20%. The migration velocity trends under these two thermal gradients were similar: all rates decreased with increasing area density. This indicates that for a surface with microdimples, increasing the area density obstructs thermally driven migration.

4. DISCUSSION

4.1. The Circle-Shaped Migration. Young’s equation defines the force balance between the tension existing at a solid−liquid (γSL), solid−gas (γSG), or liquid−gas (γLG) interface and the contact angle (θ). A simplified case is shown in Figure 7 for a droplet attached to a level substrate with omnidirectional temperature gradients, where variations in the interfacial tension at the solid−liquid surface are generated, i.e., the solid−liquid interfacial tension (γSL2) at the front (periphery) of the droplet is greater than that (γSL1) at the rear surface. This imbalance results in a traction vector that causes the droplet to migrate from a warm region toward a colder region. Meanwhile, the internal force of the droplet acting on the adjoining liquid provides an equilibrium condition in the polar angle section (dϕ), contributing to the homogeneous omnidirectional movement. Due to the finite volume of a droplet, residual liquid in the central region will become less probable as the migration diameter increases. Consequently, the droplet will migrate in the form of a circle, just as the experimental results show in Figure 3a.

However, most solids are naturally rough, and defects on the solid surface can pin the contact line of a drop on the surface. This will cause the profile of the droplet to become asymmetric.
with respect to its contact angles and a Laplace pressure difference between the front and the rear boundaries to be created. The inner pressure of the droplet can be estimated using the following:

\[ P = P_0 + \gamma / R \]  

(2)

where \( P \) is the inner pressure of the droplet, \( P_0 \) is the outer pressure of the droplet, \( R \) is the solid–gas interfacial curvature of the droplet in the \( z-r \) section, and \( \gamma \) is the surface tension.

The differential form of eq 2 is

\[ \frac{dP}{dr} = \frac{d\gamma}{R \, dr} - \frac{\gamma \, dR}{R^2 \, dr} \]  

(3)

When considering the influence of the interfacial curvature of the droplet on the inner pressure, the pressure gradient in the droplet simplifies to

\[ \frac{dP}{dr} = -\frac{\gamma \, dR}{R^2 \, dr} \]  

(4)

As mentioned above, the droplet migrates from warm to cold regions, which causes the advancing contact angle (\( \theta_a \)) to surpass the receding contact angle (\( \theta_r \)). Therefore, the curvature in the \( z-r \) section of the advancing meniscus is less than that of the receding meniscus. As indicated in eq 4, a Laplace pressure difference between the front and the rear boundaries of the expanding droplet is produced, yielding a hydrodynamic force in the droplet that resists migration. Meanwhile, the temperature of the droplet decreases during the migration process, which increases the viscosity and solid–liquid interfacial tension (\( \gamma_{SL} \)), and produces traction on the droplet. Eventually, this resistance halts the migration.

4.2. The Effect of Microdimple. The situation becomes quite complex when the surface is structured by a dimple pattern. Microscopic observations of the advancing boundary of the droplet were performed to gain insight into the dimple effect. As shown in Figure 8a, when the paraffin oil reached the edge of a dimple (300 \( \mu m \) in diameter and 15 \( \mu m \) in depth), its flow was obstructed, and the advancing boundary line was greatly deformed. With time, the quantity of liquid accumulated by the edge of the dimple increased, as shown in Figure 8b. The liquid then flowed into the dimple (Figure 8c) and finally migrated past the feature, as shown in Figure 8d.

According to eq 3, at the deformation boundary line of the droplet, an inner pressure is generated that is higher near the advancing edge. This pressure gradient creates an inner resistance to flow that obstructs migration over the dimple. Moreover, when the depth of a dimple increases, the energy necessary to overcome that feature is augmented.

4.3. The Effect of Dimple Density. Additional observations were made using a textured surface with different area densities of 5% and 20% under a uniform thermal gradient of 2 \( \degree C/mm \). The diameter and depth of the patterns were 300 and 15 \( \mu m \), respectively, and the droplet migrated in the horizontal direction. As shown in Figure 9a, when the area density was 5%, the droplet migrated to the dimples, where its movement was obstructed by the feature edge. The liquid gathered between two dimples (the intermediate zone), and the subsequent flow served to increase the height of the paraffin oil (Figure 9a1). Eventually, the liquid front continued along the surface toward the next set of dimples (Figure 9a2). This liquid front produced the traction necessary to guide the retained liquid between the two dimples and on to a colder region. However, when the area density was 20%, the phenomenon observed was vastly different, as is shown in Figure 9b. Still, the droplet was retained by the dimple edge and then gathered between features (Figure 9b1). Figure 9b2,b3 shows that the liquid did not spread through the intermediate zone until the droplet passed the dimples, which indicates that a high area density of dimples has the ability to obstruct flow even in the smooth region between features.

To aid in the description of the mechanism, sketches of the liquid migrating on these two surfaces are shown in Figure 9a,b. The existence of microdimples deforms the advancing boundary, which suggests that they provide a force (\( F_{obstruct} \)) resistant to the migration of the droplet; the more dimples there are, the greater the overall resistance is. Moreover, as the liquid gathers in the intermediate zone, the advancing boundary deforms, as shown in Figure 9a,b. The deformation curvature radius is smaller in cases of high area density than in the lower area density, which results in a larger hydrodynamic force (\( F_r \)) to resist migration.

Therefore, patterned microdimples are a way to obstruct liquid migration that is caused by omnidirectional thermal gradients, particularly when the features are of large depth and high area density.

5. CONCLUSIONS

In this study, experiments were carried out to investigate the effects of microdimple patterns on the migration behavior induced by omnidirectional and unidirectional thermal gradients. The geometric parameters of microdimples and

Figure 7. Cross-section of a three-dimensional liquid migrating on a surface defined by cylindrical coordinates; the temperature decreases linearly in the polar direction.

Figure 8. Digital images of a droplet spreading over a dimple.
interfacial flowing near the dimples were studied. Three conclusions can be drawn from this study:

1. The pattern of microdimples can impede thermal capillary migration under omnidirectional thermal gradients.
2. The deformation contact line of an advancing edge, induced by the dimple, creates a resistance that slows migration over the dimple.
3. The existence of microdimples provides an obstruction force ($F_{\text{obstruct}}$) and generates a hydrodynamic force ($F_{\gamma}$) in the droplet that increases with the area density and amplifies the resistance to migration.

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**Notes**
The authors declare no competing financial interest.

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