Original Article

Institution of MECHANICAL ENGINEERS

Journal of ENGINEERING TRIBOLOGY

Insights into the effect of thermocapillary migration of droplet on lubrication

Proc IMechE Part J:
J Engineering Tribology
2016, Vol. 230(5) 583–590

DOI: 10.1177/1350650115607895
pij.sagepub.com
SAGE

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Abstract

Thermocapillary migration, as a liquid lubricant loss mechanism, will lead to the failures of moving mechanical assemblies due to lack of lubricant. The purpose of this study was to determine the influence of thermocapillary migration of droplet on surface lubrication properties. An experimental set-up was designed to investigate the migration behavior of paraffin oil driven by temperature gradient. Friction tests were carried out to evaluate the influences of lubricant migration on tribological performance. Aspects of the temperature gradient, oil volume and initial migrating time were taken into account. The experimental results showed that the increment of temperature gradient and oil drop volume can both enhance the average velocity of drop migration, while the average velocity decreases over time. Temperature gradient exhibits the dominated effect on surface lubrication properties and starvation first takes place at the highest temperature gradient. In addition, a transition of wear mechanism from an abrasive to adhesion wear is observed in particular situations.

Keywords

Surface migration, temperature gradient, lubrication, wear, space tribology

Date received: 1 May 2015; accepted: 1 September 2015

Introduction

Friction and wear are unavoidable in mechanical systems with moving surfaces. Lubrication is always employed to completely or partially separate the friction surfaces by selectively introducing an interfacial medium (lubricant) that minimizes friction and wear. Most lubricants are fluids, yet they can also be solid, or gas.[1] It is universally acknowledged that fluid lubricant will occupy its dominant position in the foreseeable future. In fluid friction, the surfaces are separated by a viscous liquid and the modes of lubrication may be subdivided into boundary, mixed and hydrodynamic domains.[2] To function properly in a lubricated contact, a liquid lubricant has to possess certain physical and chemical properties. But one thing is for certain: the lubricant should always be maintained at the friction area.

Nowadays, with the development of space cause, space lubrication, which is one of the basic technologies of spacecraft, has been becoming far more pivotal. NASA reported that many mechanical failures occurred in spacecraft were caused by lubrication problems.[3] Though solid lubricant has been used for decades, many moving mechanical assemblies (MMAs) still rely on liquid lubricant to provide reliable, long-term performance under high load, high speed and low torque conditions.[4]

Typically, MMAs are initially lubricated with a small charge (mg) that is supposed to last the entire mission lifetime, often well in excess of 5 years.[5] Avoiding lubricant loss is one of the top priorities[6] and evaporation is a main way of oil loss in space environment.[7] Lubricant condensation may occur once molecules redeposit themselves elsewhere, which will damage or impede function of another component, for example, on lenses or optical windows.[8]

Aside from evaporation, surface migration or creep is another escaping manner for lubricant over long lifetimes of operation. The migration refers to the phenomenon that the lubricant freely expands on a contact surface without any action.[9] Generally, the migration is caused by surface tension. Since the surface tensions of most metals are much higher than that of liquid, the adhesion work between metal surface and oil molecules could be higher than the cohesive work of lubricant molecules. Thus, the interaction

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between liquid and solid can make liquid spread on the solid surface.

Obviously, low surface tension is usually associated with lubricant migration, which is beneficial since it promotes wetting of the surface. However, as the lubricant migrates away from the contact region excessively, it can lead to oil starvation in the contact zone. In addition to space mechanisms, the phenomenon should be carefully considered in other aspects, such as magnetic recording media,[10] the flip-chip and hard disk industries,[11] in which the migration of lubricant films has strong effects on device performance. To prevent the migration loss, a layer of anticreep film with a lower surface tension should be coated on the surface of component or choosing lubricant with a higher surface tension.[12]

Up to now, most of the reports on the migration of droplet lie only on a theoretical level[13–19] and a few by experimental studies. Xie et al.[20] carried out experiments on the Marangoni migration of drops in a microgravity environment. The lubricant migration rate on the hard disk surface was investigated by Cheng et al.[11] and it showed that the rate of lubricant migration increases as molecular weight decreases. Dai et al.[21] showed that the surface roughness and orientation impact on the thermocapillary migration of a droplet.

Limited information exists on the surface migration characteristics of lubricant oils, which makes it impossible to deep understand the effects of migration on lubrication in real operating mode. During the migration procedure, what is the dominate factor that influences the tribological behavior? And how about the failure type and wear mechanism? There is little knowledge about this. So the purpose of this work is to investigate the effects of oil migration on its lubrication behaviors. To enhance the migration velocity, a temperature related thermocapillary migration of droplet was adopted on substrate surface, in which the liquid can spread along the direction of temperature gradient.[22] In addition to the oil migration, more attention was paid on the lubrication performances of the rubbing surface under different oil migrating conditions.

Experimental

The Marangoni effect is a phenomenon in which a surface tension gradient drives liquid droplet flow to regions of high surface tension to form thin liquid films.[23] Previous studies have shown that temperature gradient, which produces a gradient of interfacial tension, exerts a hydrodynamic force that moves the droplet from the warmer to colder regions.[17]

In this article, oil migration induced by the temperature gradient was adopted. The experiment was performed using a substrate of 316 stainless steel with the dimensions of $100\,\text{mm} \times 30\,\text{mm} \times 2\,\text{mm}$ and average surface roughness Ra of $0.02\,\mu\text{m}$. Two temperature-controlled blocks were fixed on the ends of the substrate (see Figure 1). One block was heated by an embedded ceramic plate heater to the desired temperature. The other was thermoelectric cooler, by which the end surface of substrate could be maintained at a constant temperature of 10°C. Using the blocks, a temperature gradient could be generated along the length of the substrate and a digital video was employed to record the oil migration process. To ensure the migration behavior not caused by the chemical reaction of an additive, the pure paraffin oil with carbon chain length of ten was chosen for all experiments.

Tribological experiments were performed using a reciprocating sliding tribometer (Sinto Scientific, JAP) and the schematic diagram of the apparatus was shown in Figure 1. It consisted of a stationary

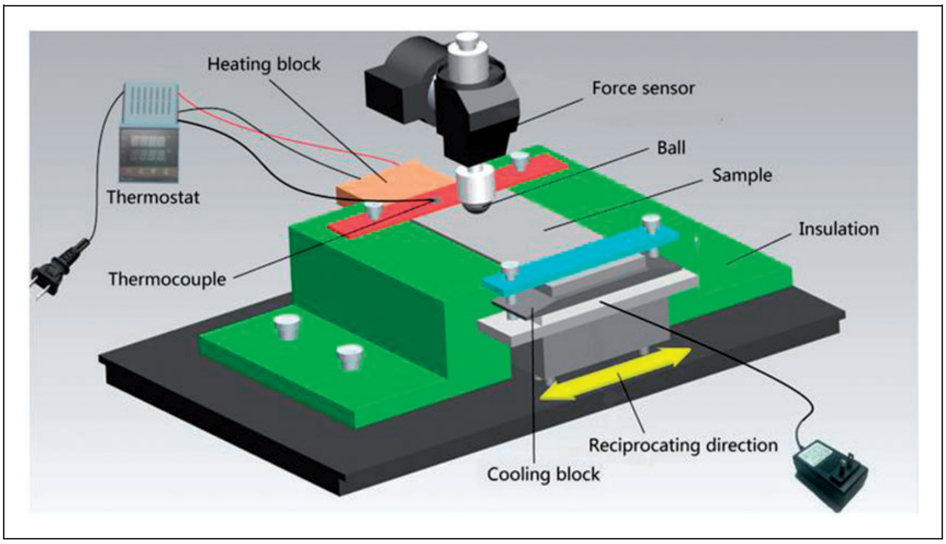

Figure 1. Schematic diagram of the apparatus.

holder where a 304 stainless steel ball with a diameter of 10 mm and Ra of 0.012 μm was placed and a reciprocating table where the 316 stainless steel substrate with heating and cooling blocks was mounted. The reciprocating motion was perpendicular to the direction of temperature gradient and a stroke of 40 mm with a sliding velocity of 8.3 mm/s was used. The normal load of 2 N, corresponding to the Hertzian contact pressure of 570 MPa was applied for all the experiments. The test time was 6500 s and friction coefficient curve was recorded automatically using a personal computer controlled data acquisition system.

Before each test, the specimens were ultrasonically cleaned in ethanol, rinsed with deionised water and finally blow-dried with nitrogen. When a desired temperature gradient was achieved, a certain volume of oil was inlet in the same position of the heating end and the migration process was recorded. The relation of oil migration distance–time was obtained by a subsequent image processing. The friction tests were also performed at the same position of heating end under a stable temperature gradient. Lubricant oil was dropped in the center of the contact line and it started after the oil fulfilling the fixed initial migrating time. The special test conditions are shown in Table 1. After the testing, the specimens were cleaned ultrasonically in ethanol to remove residual lubricant. The micro morphologies of the worn surface were observed by a scanning electron microscopy (Hitachi SU8010, JAP) and surface mapping microscope (Rtec instruments, USA).

Results and discussion

Figure 2 shows a typical oil migration process at different migrating times. The temperature gradient on the substrate surface was 3.67°C/mm and oil volume was 4 μL. It can be seen that when the oil was dropped on the surface, thermally driven migration took place along the direction of the temperature gradient. The migration distance for the first 20 s was about 12.7 mm and it increased to 14.3 mm at the end of 300 s. It shows that the average migrating velocity at the starting position was much higher and it decreased drastically with the diminishing temperature. This phenomenon could be caused by the oil surface tension.

Table 1. Test conditions.

Experiment temperature (°C)	20
Temperature gradient (°C/mm)	1.0–4.33
Experimental liquid	Paraffin oil
Kinematic viscosity (mm^2/s)	46
Density (g/mm^3)	0.9
Volume of oil (μL)	1–10
Initial migrating time (s)	0–300

To figure out the relation between oil surface tension and temperature, the contact angles of the oil on the surface of substrate at different temperatures were measured as shown in Figure 3. The dosage of the oil used was 3 μL and the pictures were taken within several seconds after the droplet came to an equilibrium state. As pointed in Ref. 24, the equilibrium contact angle reflects the relative strength of the liquid, solid and vapor molecular interaction. It can be seen clearly that the contact angle increases gradually with the reduced surface temperature, which indicates the increase in oil cohesion work. In other words, the surface energy of the oil increased, which might effectively suppress the oil spread. That may be the reason why the migrating velocity decreases dramatically with the decreasing surface temperature during the migration process.

Figure 4 shows the relation between the temperature gradient and migration distance for the initial migrating time of 120 s. It can be seen that the migration distance or average migrating velocity increased with the increasing temperature gradient. As

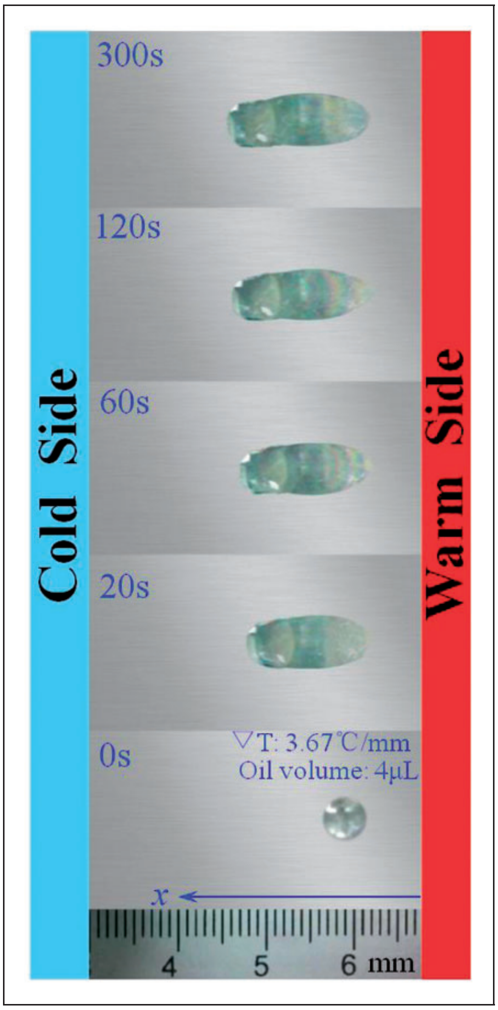

Figure 2. The image of oil migration behaviors recorded with the time. (Temperature gradient of 3.67°C/mm and oil volume of 4 μL.).

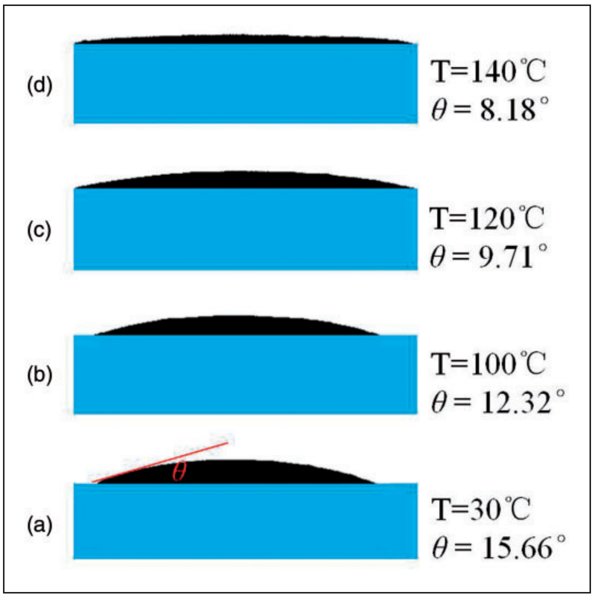

Figure 3. Equilibrium contact angle of oil at different temperatures.

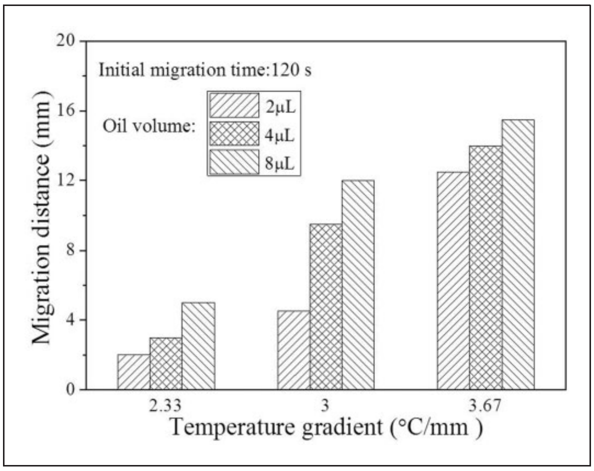

Figure 4. The relation between the temperature gradient and migration distance.

mentioned previously, the driving force for the oil flow is the surface tension gradient $\mathrm{d}\gamma/\mathrm{d}x$, which arises from the variation in the surface tension with temperature $\mathrm{d}\gamma/\mathrm{d}T$ and from the imposed temperature gradient $\mathrm{d}T/\mathrm{d}x$. The shearing stress τ generated in the film surface can be written as follow[25]:

$$\tau = \mathrm{d}\gamma/\mathrm{d}x = \mathrm{d}\gamma/\mathrm{d}T \cdot \mathrm{d}T/\mathrm{d}x$$

where γ is the surface tension of oil, T is the temperature and τ is the shearing stress. The stress causes the oil to spread towards the region of higher surface tension (the colder region). The higher stress it is, the faster average migrating velocity it appears. Therefore, the greater temperature gradient is more conductive than the lower to drive the oil migration.

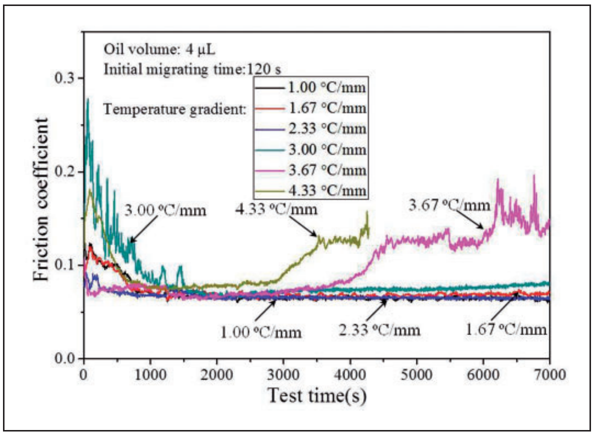

Figure 5. Evolution of friction curves under different temperature gradients.

The experimental results also show that the dosage of the oil can affect the average migrating velocity. As Fote and Slade[26] pointed out that the average flow velocity of oil film is proportional to the film thickness. With the increase in oil volume, the thickness of film rises inevitably, which leads to the increase in migrating velocity.

Figure 5 presents the typical evolution of friction coefficients of tribopairs under different temperature gradients. The dosage of the oil was 4 μL, and the tests started after the oil completing an initial migrating time of 120 s. For the six conditions, the starting friction coefficients varied between the values of 0.07 and 0.25. The higher coefficients under temperature gradient of 3.0°C/mm could be caused by a higher local surface roughness in the contact area on the substrate compared with others and the coefficient decreased gradually, showing an typical running-in process. Similar phenomenon was also observed for the temperature gradient of 4.33°C/mm. However, after running-in for 1500 s, all the coefficients went into a steady-state value of about 0.07. Distinct difference first appeared at the test moment of 2500 s and the friction coefficients under the highest gradient of 4.33°C/mm increased gradually. As time went on, the coefficients under the gradient of 3.67°C/mm also rose, which was accompanied by the formation of large amounts of wear debris near the edge of the wear scar mainly in the lower temperature side, as can be seen in the image of Figure 6(a). As mentioned before, the higher temperature gradient is conducive to form larger shearing stress, which helps to draw more lubricant oil to move out the friction region. In addition, the cohesion work between oil molecules decreases with increasing temperature, leading to the reduction in contact angles (see Figure 3) and the net effect is an accelerating spread. Therefore, the starvation inevitably happens.

However, the friction curves tended stable and the values were both below 0.1 at the lower gradient of 1.0, 1.67, 2.33 and 3.0°C/mm, which means the lubricant is still valid though much of the oil has escaped

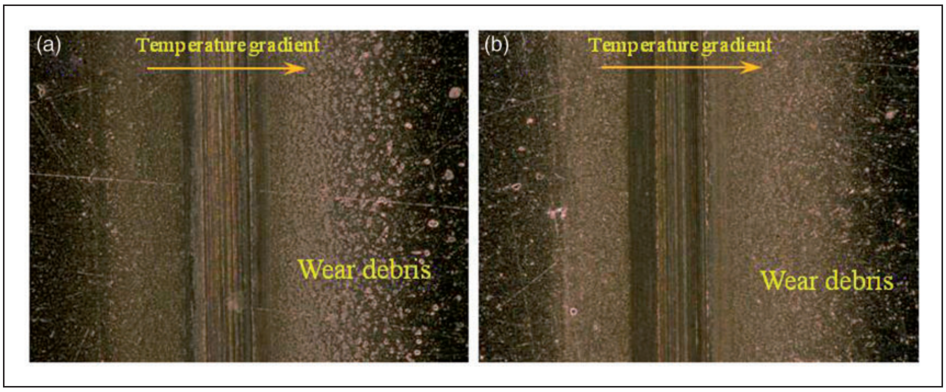

Figure 6. The images of wear debris distribution. (a) at temperature gradient of 3.67°C/mm; (b) at temperature gradient of 3.0°C/mm.

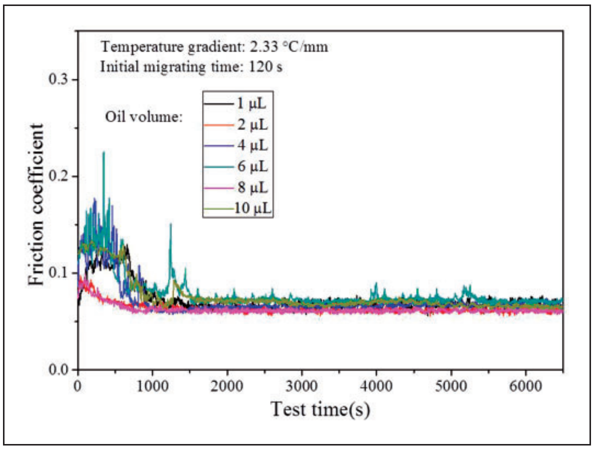

Figure 7. Evolution of friction curves under different oil volumes at temperature gradient of 2.33°C/mm.

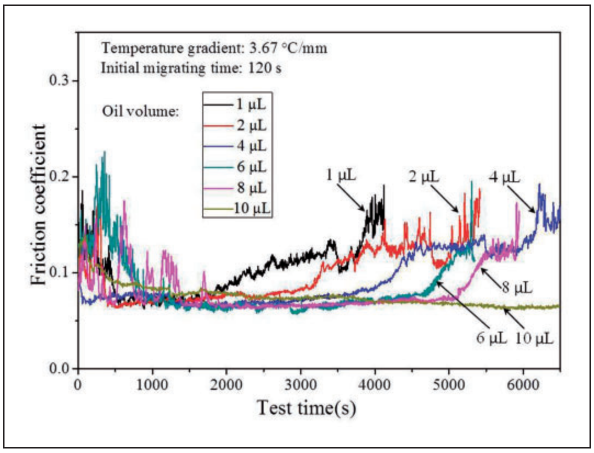

Figure 8. Evolution of friction curves under different oil volumes at temperature gradient of 3.67°C/mm.

to the low temperature regions. As can be seen in Figure 6(b), a handful of small wear debris was found at the temperature gradient of 3.0°C/mm and the size of the wear debris is so smaller than that formed at higher of 3.67°C/mm. Nevertheless, there remains slight variance between the lower gradient conditions and the friction curve obtained at 3.0°C/mm still shows higher values.

Beside the temperature gradient, the oil dosage also shows a certain impact on migration (see Figure 4). Figure 7 presents the evolution of friction coefficients using different doses of oil at the temperature gradient of 2.33°C/mm with initial migrating time of 120 s. All the friction curves remained constant after a period of testing time and the oil dosage showed no significant influence on the friction. As can be seen in Figure 4, the average migrating velocity was the slowest at the condition of 2.33°C/mm and residual lubricant depositing on the rubbing surface can sustain acceptable tribological performance throughout the operational time.

Figure 8 presents the friction curves using different volumes of oil at a higher temperature gradient of 3.67°C/mm. After running-in process, friction increment first emerged in the case of 1 μL oil lubricated condition, it continuously rose as time went by and a sharp increase was observed finally. In 2 μL case, the coefficients also showed a gradual increase with the time prolonged. As expected, the moment of coefficient increment appeared later than that of 1 μL oil condition. For the cases of 4, 6 and 8 μL, very smooth constant low friction values were observed and the time for the friction increasing was delayed further one by one. The friction behaviors under the five conditions (1–8 μL) showed a clear transition from a low value of 0.07–0.2, corresponding to the transition from the mixed into the boundary lubrication regime. When the oil volume increased to 10 μL, the coefficient still remains lower during the test time. Though the average migrating velocity increased with the increment of oil volume, the absolute account of oil maintained in the friction area might be the highest for the 10-μL oil lubricated condition, which could be the reason of the steady friction process. After comparing with Figures 7 and 8, it can be found that the temperature gradient rather than oil dosage plays a greater role on lubrication properties.

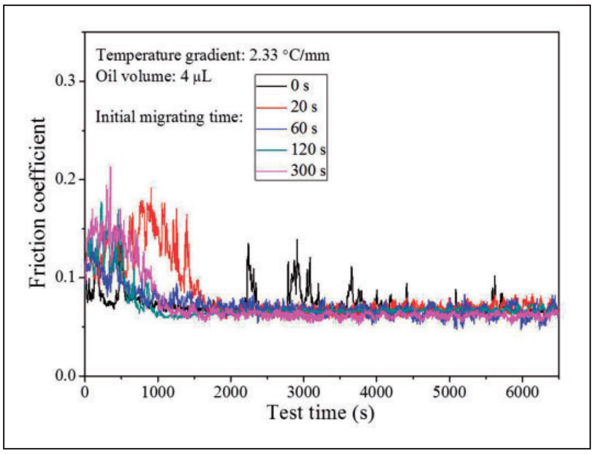

Figure 9. Evolution of friction curves under different initial migration times at temperature gradient of 2.33°C/mm.

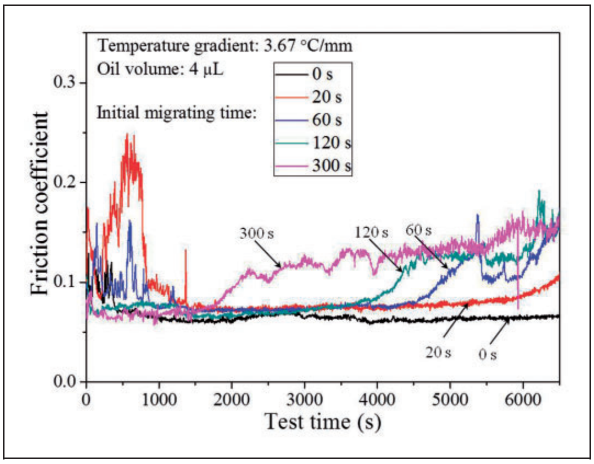

Figure 10. Evolution of friction curves under different initial migration times at temperature gradient of 3.67°C/mm.

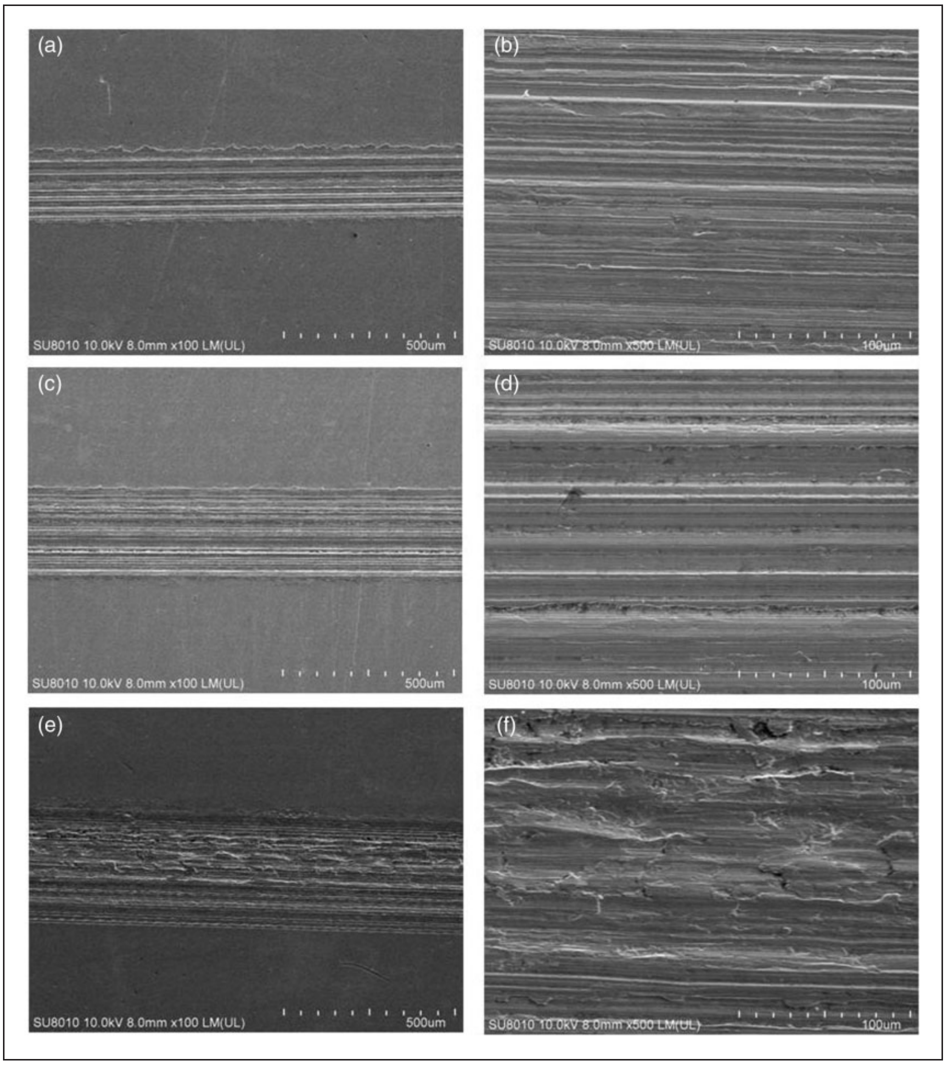

Figure 11. SEM images of the worn substrate surfaces with different initial migrating times. 20 s (a and b), 60 s (c and d) and 120 s (e and f).

Previous studies have also shown that the initial migrating time has a close impact on the oil distribution (see Figure 2). Figures 9 and 10 present the evolution of friction curves under different initial migrating times with a drop volume of 4 μL. It can be seen in Figure 9 that all the curves tend to be stable after a short time of running-in process at lower temperature gradient of 2.33°C/mm. However, significant difference was observed at a higher temperature gradient of 3.67°C/mm. As can be seen in Figure 10, after

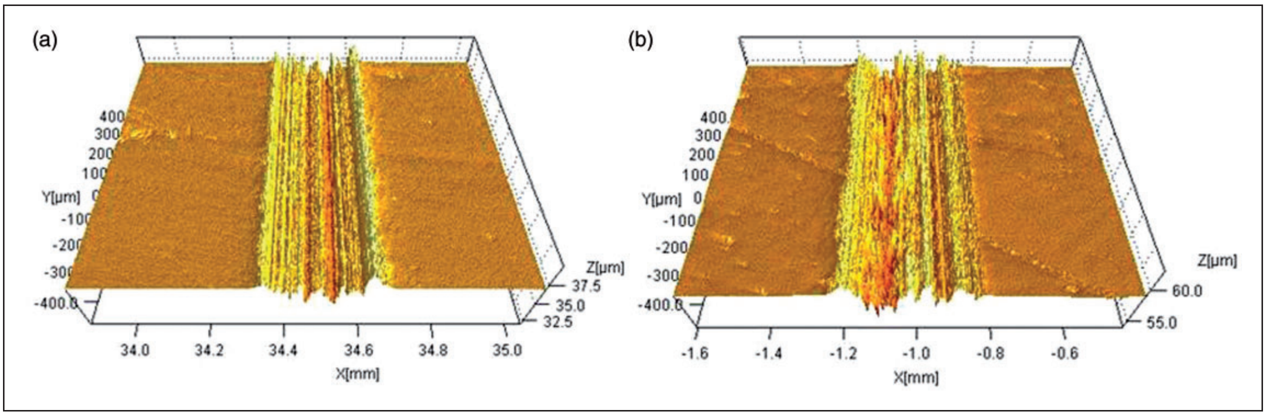

Figure 12. Three-dimensional (3D) morphologies of wear tracks with different initial migrating times. (a) 20 s and (b)120 s.

a short duration of low friction in case of initial migrating time of 300 s, a sudden friction increment is accompanied and it continuously grows till the value of about 0.16. Similar phenomenon appeared for the migrating time of 60 and 120 s. Overall, the moments of the coefficient increment were extended with the decrease in oil initial migrating time. And the friction curve, which started as the oil dropped, always kept stable.

The test results show that the oil content in the friction area is crucial to the follow-up tribological performances. In mixed and boundary lubrication, the lubricant film thickness is so narrow that direct metal-to-metal contact occurs. The frictional characteristics are determined by the properties of the interacting surfaces and the lubricant film present. The high pressure and temperature at the contact surfaces cause the formation of a boundary film, which is capable of supporting the load without major wear or breakdown. As the result shown in Figure 2, the migration distance increased with the time and more oil lost from the original oil dropped position. The oil, which can be exploited in the contact area, is vanishingly rare and lubrication failure first appeared due to the excess thin lubricant film under the maximum initial migrating time of 300 s. As time passed, thin lubricant films fractured in sequence for the initial migrating time of 120 and 60 s, corresponding to the increment of friction coefficients.

The abrasive wear mechanism was observed in Figure 11(b) and the worn surface was covered with many slight and narrow scratch lines parallel to the sliding direction. The wear of the surface with 60 s migrating time expressed through deeper grooves, with slight addition of adhesive wear (see Figure 11(d)). Contrary to the above, the worn surface with 120 s migrating time was characterized by severe adhesion and plastic deformation associated with scuffing damage visible thereon (seen Figure 11(f)), corresponding to the fast friction transition in Figure 10.

Figure 12 presents the three-dimensional morphologies of wear tracks in Figure 11 with initial migrating times of 20 and 120 s, respectively. Likewise, the worn surface in Figure 12(a) shows a mild abrasive wear with shallow grooves. However, the wear scar becomes wider and plastic deformation can be found in Figure 12(b), which corresponds to severe adhesion wear.

Thus, it can be concluded that the oil migrating time has a significant effect on the wear characteristics. As can be seen in Figure 2 the migration distance increases with the migrating time. Obviously, the less migrating time is the more oil it remains at the rubbing surface. It is known that in boundary or mixed lubrication regime, surfaces are not completely separated, resulting in surface asperity interactions. And there is no doubt that a thin oil film between the tribopairs is essential to maintain efficient lubrication throughout the operation time and to increase the friction lifetime.

Conclusions

In this article, the influences of thermocapillary migration of oil droplet on surface lubrication properties were investigated. The main results can be summarized as follow:

1. The temperature gradient and oil drop volume show strong influences on the average velocity of drop migration. And it increases with the increase in temperature gradient and oil drop volume. In addition, the average velocity of drop migration decreases dramatically during the migration process.
2. Among the three factors of temperature gradient, oil drop volume and initial migrating time, temperature gradient shows the dominated effect on the lubrication properties and starvation first takes place at higher temperature gradient.
3. At higher temperature gradient, oil drop volume presents important influence on the lubrication properties and the increase in oil amounts helps to achieve better lubrication.

4. At a higher temperature gradient, the wear mechanisms changed from a mild abrasive to severe adhesion wear with the increase in initial migrating time.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by National Natural Science Foundation of China (No. 51475241).

References

1. http://en.wikipedia.org/wiki/Lubrication
2. Totten GE. *Handbook of lubrication and tribology. Application and maintenance*. New York: Taylor & Francis Group, 2006.
3. Fusaro RL. *Preventing spacecraft failures due to tribological problems*. NASA/TM—2001-210806, 2001.
4. Sathyan K. Tribology of high speed moving mechanical systems for spacecrafts – tribological issues. *J Eng Technol* 2012; 2: 27–34.
5. Marchetti M, Jones WR, Pepper SV, et al. In-situ, on-demand lubrication system for space mechanisms. *Tribol Trans* 2003; 46: 452–459.
6. Roberts EW and Todd MJ. Space and vacuum tribology. *Wear* 1990; 136: 157–167.
7. Jansen MJ and Jones WR. Tribology for space applications. *Proc IMechE, Part J: J Engineering Tribology* 2008; 222: 997–1004.
8. Street KW. Liquid space lubricants examined by vibrational microspectroscopy. *Anal Lett* 2008; 41: 351–376.
9. Wen S and Huang P. *Principles of tribology*. China: Tsinghua University Press, 2011.
10. Nishida Y, Nishida Y, Kikkawa M and Kondo H. Behavior of lubricant migration in particulate magnetic recording media. *IEEE Trans Magn* 1999; 35: 2451–2453.
11. Cheng T, Zhao B, Chao J, et al. The lubricant migration rate on the hard disk surface. *Tribol Lett* 2000; 9: 181–185.
12. Zaretsky EV. Liquid lubrication in space. *Tribol Int* 1990; 23: 75–93.
13. Savino R, Monti R and Alterio G. Drops pushing by Marangoni forces. *Phys Fluids* 2001; 13: 1513.
14. Keh HJ, Chen PY and Chen LS. Thermocapillary motion of a fluid droplet parallel to two plane walls. *Int J Multiphase Flow* 2002; 28: 1149–1175.
15. Smith MK. Thermocapillary migration of a two-dimensional liquid droplet on a solid surface. *J Fluid Mech* 1995; 294: 209–230.
16. Zhou H and Davis RH. Axisymmetric thermocapillary migration of two deformable viscous drops. *J Colloid Interface Sci* 1996; 181: 60–72.
17. Gomba JM and Homsy GM. Regimes of thermocapillary migration of droplets under partial wetting conditions. *J Fluid Mech* 2010; 647: 125.
18. Samareh B, Mostaghimi J and Moreau C. Thermocapillary migration of a deformable droplet. *Int J Heat Mass Transfer* 2014; 73: 616–626.
19. Qin T, Tuković Ze and Grigoriev RO. Buoyancy-thermocapillary convection of volatile fluids under atmospheric conditions. *Int J Heat Mass Transfer* 2014; 75: 284–301.
20. Xie JC, Lin H, Han JH, et al. Experimental investigation of thermocapillary migration of isolated drops. *Adv Space Res* 1999; 24: 1409–1415.
21. Dai Q, Huang W and Wang X. Surface roughness and orientation effects on the thermo-capillary migration of a droplet of paraffin oil. *Exp Therm Fluid Sci* 2014; 57: 200–206.
22. Fote AA, Slade RA and Feuerstein S. The prevention of lubricant migration in spacecraft. *Wear* 1978; 51: 67–75.
23. Scriven LE and Sternling CV. The Marangoni effects. *Nature* 1960; 187: 186–188.
24. Decker EL, Frank B, Suo Y, et al. Physics of contact angle measurement. *Colloids Surf A* 1999; 156: 177–189.
25. Fote AA. *Migration of apiezon C on metal substrates under the influence of temperature gradients: mathematical model*. The Aerospace Corporation, El Segundo, CA. Report SAMSO-TR-75-300, 30 December 1975.
26. Fote AA and Slade RA. *The role of lubricant type and substrate composition in thermally induced oil migration*. The Aerospace Corporation, El Segundo, CA. Report SAMSO-TR-77-219, 6 December 1977.