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Full Length Article

Modeling and experimental analysis of thermocapillary effect on laser grooved surfaces at high temperature

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ABSTRACT

Spreading behaviors of oil on laser grooved stainless steel 316L surfaces were studied theoretically and experimentally at high temperature with consideration of thermocapillary effect. A mathematic model of droplet spreading on grooved surfaces was developed taking into account of thermocapillary, groove capillary, thermal viscous effect and surface tension. Then, numerical analysis and experiments were carried out on laser grooved surfaces with different temperature gradient and change of droplet center temperature from 24 to 200 °C accordingly. It was shown that the present model agreed well with the experiment in predicting oil droplet thermocapillary spreading. The initial acceleration phase of oil spreading was proved more and more significant with temperature gradient increasing, producing maximum velocity form 5.8 to 15.93 mm/s with the increasing of temperature gradient from 0 to 3.72 °C/mm. Besides, the oil spreading in the opposite direction of temperature gradient was faster than that in the direction of temperature gradient, and the distance difference increased form 0.06 mm to 1.16 mm with the increasing of temperature gradient from 0.45 to 2.12 °C/mm after 1 s spreading, which illustrated that thermocapillary effect was gradually weakened with the corresponding temperature rising. Further, oil thermal viscous effect was proved as the main reason for this weakening. Groove capillary should be the active force for the directional spreading and even directing oil to high temperature regions, especially under high temperature gradient conditions.

1. Introduction

Thermocapillary effect is a common phenomenon on the lubricating engineering surfaces such as bearings, leading lubricant migration from high temperature region to the lower, causing insufficient lubrication [1,2]. There have been many attempts to stop the liquid migration, including improving the surface tension, modifying surface roughness and balancing temperature gradient [3–5]. In theory, liquid migration takes place when there is a gradient of surface tension and it is referred to as the thermocapillary in the cases where the surface tension varies with the temperature [6,7]. Surface directional grooves have been proved presenting guiding effect on liquid motion and accelerating this motion owing to the capillary [8–12], which maybe provide a potential way to counterbalance the thermocapillary effect.

The thermocapillary effect, as a widespread problem, has aroused people's attention [13,14]. Dai et al. [15] experimentally demonstrated that microdimples had a significant obstructive effect on liquid migration with an omnidirectional thermal gradient and dimples with deeper depth and greater density showed more obvious obstructive effect. Besides, Grützmacher et al. [16] showed the liquid spreading parallel to the surface patterning was accelerated and pinned perpendicular to the patterns by comparing the spreading velocity with temperature gradient 2 °C/mm.

To analyze the spreading behaviors of droplet, lubrication theory was generally adopted and temperature dependence of viscosity and surface tension were taken into account simultaneously [17–19]. Karapetsas et al. [17,18] studied the thermocapillary motion of a droplet on both inclined and horizontal nonisothermal plate and described the evolution of drop profile and extent of spreading under different temperature gradients. Dai et al. [19] computed droplets migration velocity on smooth surfaces with temperature gradient 2.6 and 3.0 °C/mm respectively, which was in good agreement with the experimental results. Besides, a linear relationship between liquid spreading distance and square of time was discussed considering the groove capillary on the basis Washbrun's work [20–23]. However, temperature problems have not been focused in the published work, which makes it difficult to precisely predict the spreading behavior of a droplet on grooved surfaces, especially under the high temperature gradient conditions.

In this manuscript, a mathematic model of droplet spreading on grooved surfaces was developed taking into account of thermocapillary, groove capillary, thermal viscous effect and surface tension. Spreading behaviors of oil on both smooth and laser grooved stainless steel 316L

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surfaces were recorded under different temperature gradient conditions. Besides, the oil spreading in the direction of temperature gradient and the opposite direction was analyzed numerically and measured experimentally in order to contrast capillary and thermocapillary.

2. Theoretical model

F_γ	capillary force, N
γ_l	surface tension, N m^{-1}
w	width of the groove, m
h_0	depth of the groove, m
P_s	additional stress, Pa
R	radius of curvature, m
V_{up}	volume of segment, m^3
h	hight of spherical segment, m
θ_0	contact angle of smooth surface, °
A	area ratio
w_0	non-grooved width, m
V_0	volume of whole droplet, 2.0×10^{-9} m^3
V_{down}	volume of liquid immersed into the groove, m^3
F_η	viscosity resistance, N
η	viscosity of liquid
C_1	Geometry parameter about surface morphology
ρ_0	density of liquid
V	Molar volume, m^3 mol^{-1}
T_c	critical temperature, K
k	Eotvos-Ramsay Coefficient, 2.2×10^{-7} J/(K·mol$^{2/3}$)
F_{th}	Thermocapillary force, N

In the theoretical analysis, we focused on the finite volume droplet positioned on grooved surfaces under temperature gradient conditions, which was shown in Fig. 1. Here, capillary, thermocapillary, additional stress and viscosity resistance were considered.

2.1. Capillary force

Capillary force was given by the negative gradient of total mechanical or capillary energy [24], which was expressed as Eq. (1) for groove morphology.

$$F_\gamma = \gamma_l[(w + 2h_0)\cos\theta_0 - w] \tag{1}$$

where F_γ is capillary force, γ_l is surface tension of liquid, w is groove width, h_0 is groove depth and θ_0 is contact angle of liquid on smooth surface. The variation of contact angle and surface tension of liquid with temperature was considered in the computing.

2.2. Additional force

Assume that the base line of droplet was circular and the remnant droplet was always part of the ball. Young-Laplace Equation was used to describe the additional stress of curved surface as follows.

$$P_s = \frac{2\gamma_l}{R} \tag{2}$$

where P_s was additional stress, and R was radius of curvature. The additional force was described as

$$F_s = \frac{2\gamma_l}{R} w h_0 \tag{3}$$

In order to obtain the radius of curvature, assume the contact angle θ_0 keep consistence with the droplet spreading. Thus, the expression of the volume of remnant droplet above the groove V_{up}, was obtained.

$$V_{up} = \pi h^2 \left(R - \frac{h}{3}\right) \tag{4}$$

where h is the thickness of the remnant droplet and it can be calculated by

$$h = R(1 - \cos\theta_0) \tag{5}$$

Besides, the actual spreading area of liquid depends on the area ratio of grooved area and non-grooved area, which was defined as A.

$$A = \frac{w}{w + w_0} \tag{6}$$

where w_0 is non-grooved width. Assuming liquid fills the groove completely, the volume of liquid immersed in the groove, $V_{down,}$ was obtained.

$$V_{down} = \pi \cdot x^2 \cdot A \cdot h_0 \tag{7}$$

where x is spreading distance.

So, the volume of remnant droplet, $V_{0,}$ can also be obtained.

$$V_{up} = V_0 - V_{down} \tag{8}$$

where V_0 is the whole droplet volume.

Further, institution of Eqs. (5)–(8) into (4) gave the expression of the radius of curvature.

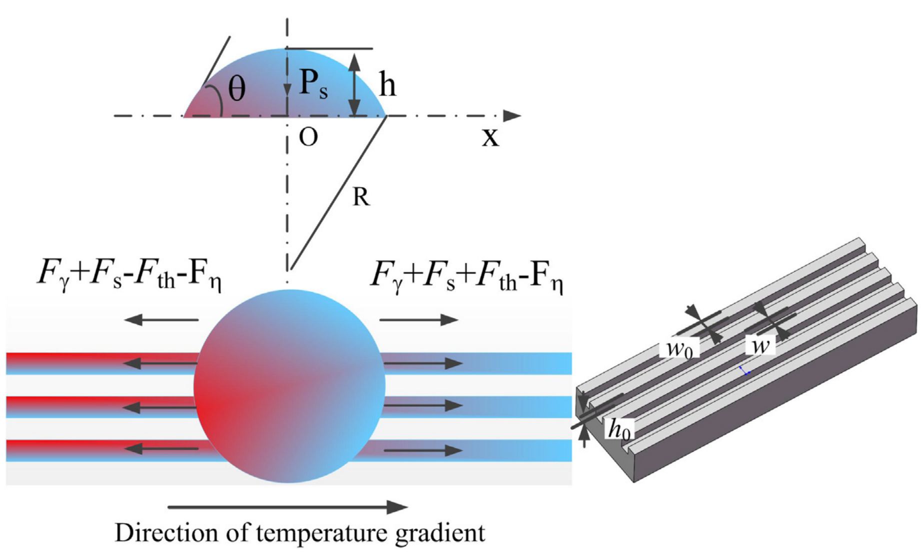

Fig. 1. Schematic diagram of droplet on grooved surface with temperature gradient.