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Guiding lubricant on stainless steel surfaces by channel-like structures fabricated by roller- and micro-coining

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HIGHLIGHTS

- Manufacturing of single- and multi-channel surfaces on stainless steel by coining.
- Increasing spreading velocity with deeper and wider single channels.
- Multi-channel surfaces can overcome Marangoni force and prevent lubricant migration.
- For multi-channel surfaces, the periodicity has the strongest influence.

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ABSTRACT

Guiding lubricant back to the tribological contact or preventing lubricant migration out of the contact zone can be considered as an efficient approach to significantly reduce friction and wear in machine components. This paper aims at studying the spreading behavior of an additive-free lubricant (PAO 4) on coined stainless steel surfaces (AISI 304) under the effect of a controlled temperature gradient of 2 °C/mm. Single channels and multi-channel samples were manufactured by roller coining and hot micro-coining, respectively. A systematic study of the influence of the geometrical parameters on the resulting spreading behavior has been performed. For polished reference samples, a preferential oil spreading parallel to the temperature gradient was observed which can be correlated with Marangoni forces. For single channels, the spreading velocity increases with an increase in structural depth. Multi-channels show a pronounced anisotropic spreading behavior. Lubricant migration towards the colder side of the sample can be prevented if the structures are oriented perpendicular to the temperature gradient. For multi-channel surfaces, the spreading behavior parallel to the temperature gradient is greatly influenced by the periodicity and area density. Samples with a smaller periodicity and greater area density show a higher spreading velocity of a droplet.

1. Introduction

Surface structuring of metallic surfaces is a promising approach to optimize their tribological or wetting behavior. In terms of tribology, surface structures can be directly applied to the contact area to significantly reduce friction and/or

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wear [1–4]. However, those structures are likely to wear off with time thus losing their intended functionality. In contrast to that, applying surface structures in the close proximity of the contact area where they are not subject to wear creates the possibility to indirectly affect the tribological performance by preventing lubricant migration out of the contact area or guiding lubricant back into the contact area [5–7]. It is well known that the temperature in the contact area of a tribological contact increases due to frictional heating. At local contact spots rather high interface temperatures tend to occur. As a consequence, a temperature gradient evolves thus resulting in a surface tension gradient which can lead to lubricant migration out of the contact area and thus to insufficient lubrication [8]. In rotating machine components, centrifugal forces might additionally drive the lubricant out of the contact zone, also leading to lubricant starvation [9,5].

Therefore, a directional spreading behavior on surfaces is of great interest for tribological applications and microfluidic technologies in which a liquid is transported in open channels. In those channels, capillary forces become important for transporting liquid since conventional pumping methods fail [10]. There are many methods to generate such open channels including photolithography, laser surface patterning or mechanical processes like grinding or embossing [7,11,12]. It is worth to emphasize that the directional spreading behavior depends on the material, the surface chemistry and finally the size of the fabricated structures [13,14].

Using standard photolithographic methods, Seemann et al. fabricated grooves with a rectangular cross-section in silicon having a depth between 100 and 900 nm and a width between 400 nm and 3 μm. They demonstrated that the contact line of the liquid droplet is pinned by the edges of the structures which makes it possible to confine the liquid inside the channels and guide it along them [15]. A number of manuscripts deal with the spreading behavior of liquids on laser patterned surfaces [16,7,13]. Rosenkranz et al. showed an anisotropic spreading behavior for channel-like surface patterns fabricated by direct laser interference patterning (DLIP). Thereby, the anisotropy of the spreading behavior increases with decreasing distance between the channels which can be traced back to more structures in contact with the liquid and therefore a stronger pinning of the contact line [16]. Another study deals with the wetting properties of water on micro-grinded silicon surfaces. The grooves on the surfaces lead to an anisotropic spreading behavior with a preferential spreading along the major axis of the grooves whereas the highest anisotropy is reached for the deepest structures. The reason for the observed anisotropy was attributed to a pinning effect perpendicular to the grooves due to sharp micro-groove tops [17].

The flow behavior of Newtonian fluids in open micro-channels can generally be described by the Lucas–Washburn equation [18–20]:

$$l^2 = \frac{\gamma r \cos\theta}{2\eta} t \tag{1}$$

where l is the position of the traveling meniscus along the channel, γ is the surface tension of the liquid, r is the channel radius, θ is the static contact angle of the liquid on the channel wall, η is the dynamic viscosity of the liquid phase and t is the time. This indicates that the velocity of the liquid inside the channels decreases following a $\sqrt{t}$ behavior. A general expression has been found by Rye et al. to describe the fluid behavior in open micro-channels [21]:

$$l^2 = K(\alpha, \theta) \frac{\gamma T}{\eta} t \tag{2}$$

where $K(\alpha, \theta)$ is a geometric term which depends on the groove angle α and the contact angle θ and T is the structural depth. Eq. (2) shows that the structural depth of the grooves represents a decisive factor regarding the influence on the liquid penetration into channels.

The spreading behavior of liquids on surfaces with temperature gradients has also been investigated in the past. Chen et al. explored the droplet migration of several organic liquids on silanized surfaces under the influence of a temperature gradient between 2 and 4 °C/mm. They verified that the droplets always move towards the colder side of the sample and therefore towards regions with high surface tension due to thermo-capillary forces. Furthermore, they demonstrated that the contact angle hysteresis causes a pinning of the droplet which prevents spreading below a certain droplet radius [22]. The force by an imbalance of the surface tension along the droplet may even be high enough to cause a droplet to move uphill on an inclined surface against the force of gravity. Chaudhury and Whitesides induced such a behavior of a water droplet by chemically generating a gradient in surface free energy on silicon wafers [23]. Grützmacher et al. investigated the spreading behavior of Poly-(alpha)-olefin (PAO) oil on laser-patterned steel surfaces with a temperature gradient of roughly 2 °C/mm. They demonstrated a spreading behavior of oil from the hot to the colder side of the sample due to Marangoni forces. Thereby, the spreading velocity parallel to the structures was increased with greater structural depths which can be explained with higher capillary forces [7]. Furthermore, if the groove-like patterns are oriented in a direction perpendicular to the temperature gradient, the spreading velocity can be slowed down because of pinning of the droplet at the edges of the structures.

In this study, the effect of micro-coined surface structures on the spreading behavior of an additive-free PAO oil with a kinematic viscosity of 4 cSt (PAO 4) and a viscosity index of 124 on stainless steel surfaces under the influence of an applied temperature gradient is investigated. Thereby, single channels manufactured by roller-coining and multi-channels fabricated by hot micro-coining are studied. In this context, the structural depth as well as width and periodicity of the structures are varied. In order to measure the droplet spreading an especially designed test rig is used which allows for a precise control of the temperature gradient and the recording of the spreading dynamics.