Regulation and control of wet friction of soft materials using surface texturing: A review

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Abstract: Surface texturing is a smart strategy that is commonly used in nature or industry to improve the tribological properties of sliding surfaces. Herein, we focus on the recent research progress pertaining to the wet friction modification of soft elastomers via texturing. To consider the pertinent physical mechanisms, we present and discuss the fundamentals of wet sliding on soft surfaces (including dewetting and wetting transitions in compliant contacts). Subsequently, we consider the methods in which the characteristic textures regulate and control wet sliding behaviors on soft surfaces; these textures range from conventional patterns of dimples to bioinspired architectures and can either positively or adversely impact the interfacial friction force. Furthermore, we briefly address the perspectives, potential applications, and challenges of texture design for modifying the friction characteristics of soft materials.

Keywords: soft material; surface texture; wet sliding; friction

1 Introduction

Natural organisms typically employ smart strategies such as developing various types of near-surface architectures in the millimeter to nanometer range to considerably modify the surficial characteristics (e.g., friction, adhesion, and wetting) of their epidermises [1]. Numerous examples can be found in nature, including lotus leaves [2], shark skins [3], gecko toe pads [4], and moth eyes [5]. Thus, scientific efforts have been made to understand the underlying mechanisms, fabrication of synthetic structures, and designs of these novel surfaces. In particular, material surfaces are typically supplemented with structures to improve their tribological performance (often referred to by tribologists as creating “textures”); the friction is geometry-dominated rather than surface-chemistry dominated [6, 7]. This provides opportunities for new areas of surface designs and modifications [8].

The use of surface textures to enhance tribological performance is not new. An early successful case of such engineering is the honing of cross-reticulated structures on engine cylinder liners in the 1940s [9]. However, at that time, texture was a relatively vague concept. Evans and Bryan [10] quoted a remark from a high court judge: “I cannot define it, but I know it when I see it” to illustrate the definition of textures. In 1996, Hamilton et al. [11] reported that the surface-texturing of micro-asperities can be performed to achieve micro-hydrodynamic (HD) bearings for wet sliding. This idea piqued the interest of researchers, and many important studies across various disciplines have been published. Etsion and Burstein [12] theoretically ascertained the positive effects of dimples
for promoting the load-carrying capacity of a lubricant; they increased the seal lifetime threefold by using appropriate design parameters [6]. Owing to the development in microfabrication (e.g., laser, reactive ion etching and electrochemical machining), surface texturing for tribology has been experimentally investigated by employing various materials (e.g., steel, alloy, and SiC) while considering design optimization (e.g., shape, profile, size, and arrangement) [13–16]. The beneficial attributes afforded by surface texturing include anti-friction, wear resistance, anti-seizure, improvements in lubrication transition, and rapid running-in processes [14, 17–21]. Furthermore, several comprehensive overviews have been published [7, 22–24].

Texturing for tribology has progressed rapidly and is understood well; however, it is primarily applied to reduce friction on hard surfaces. The effect of texture design on the friction behavior of soft elastomers (such as polymer, rubber, gel, and tissue) and whether friction modification will still be triggered (similar to the case of hard materials) are yet to be investigated. Studies in which such issues are addressed are scarce, and the tribological application of texturing on soft elastomers remains challenging. Compared with hard materials, soft elastomers are characterized by high deformation and a low-energy surface. This enables them to establish compliant contacts with their counterparts, thereby potentially facilitating sandwiched film dewetting under wet contact [24–26]. This implies that “dry contact” may occur even in wet sliding, and that the interfacial friction during a contact may be a result of the competition between the dry area and lubricant film. Martin et al. [25] identified a superior wetting transition in compliant contacts; it was found to depend on the crucial sliding velocity and was more complicated than that observed on hard surfaces.

With respect to the role of textures on the sliding friction of soft surfaces, the investigations indicate that the texture design can smooth the friction curve of soft surfaces, reducing the instability of sliding (e.g., the stick–slip and Schallamach waves induced by adhesive contact) [26–28]. The typical shape designs used in texturing reduce the friction force during wet soft sliding [29, 30]; however, the sliding mechanism remains elusive, because a wetting transition synergized by textures is present in the sliding regime [31]. In addition, recent findings regarding the structured epidermises of certain amphibians (e.g., tree frogs and newts) indicate that texturing can produce a high friction force in lubricated sliding [32, 33]. The toe pads of amphibians exhibit a polygonal microstructure of cells separated by channels that can expel fluid from the contact area of the epidermis to the substrate, thereby preventing hydroplaning and facilitating high boundary friction [34]. Based on these findings, various biomimics of polygonal textures have been designed and investigated to achieve large friction forces on wet-slippery soft surfaces [35, 36]. Certain fibrillar design textures inspired by geckos or insects can enhance friction forces in dry sliding [37–39]; however, the interest in this area is limited to wet surfaces [40]. In general, surface texturing enables the frictional effects on wet soft surfaces to be regulated or altered (increase or decrease); however, further mechanisms need to be investigated. Because of the wide potential applications of texture designs on wet soft surfaces (such as tires [41], wipers, and robots [36, 42, 43] and intelligent wearable devices [43–45]), the current trends and limitations should be analyzed.

The present paper summarizes the current investigations on the texture design for friction modulation on soft surfaces during wet sliding. We first focus on the fundamentals of sliding on wet soft surfaces, including the origins of the dewetting behavior and wetting transition in compliant contacts (Section 2). In Section 3, we discuss two representative textures, namely dimples and hexagonal pillars, which can increase and decrease the friction on wet soft surfaces; subsequently, we also discuss physical mechanisms and optimization designs. Finally, in Section 4, we present the potential applications and future perspectives of soft textured surfaces.

2 Fundamentals of sliding friction on flat soft surfaces under wet conditions

2.1 Squeezing of films in compliant contacts

According to previous studies [46–48], the interfacial friction of soft elastomers under wet sliding conditions (Fig. 1(a)) depends significantly on the properties of
the intercalated liquid film, which can be indicated by the sign of the spreading parameter $S$. $S$ compares the interfacial energies between “dry” and lubricated contacts, as $S = \gamma_{SR} - (\gamma_{SL} + \gamma_{LR})$, where $\gamma_{SR}$, $\gamma_{SL}$, and $\gamma_{LR}$ denotes the solid/rubber, solid/liquid, and liquid/rubber interfacial tensions, respectively [46] (Fig. 1(b)). If $S \geq 0$, the wedged film between the elastomer and its counterpart is stable, serving as a continuous lubricant under sliding. By contrast, when $S < 0$, the film is unstable and collapses easily to produce dry contact. This is known as dewetting [49].

The velocity of the dewetting process $v_d$ can be expressed as [50]:

$$v_d \propto \frac{\eta^2}{\eta E e}$$  \hspace{1cm} (1)

where $\eta$ is the liquid viscosity, $E$ is the elastic modulus of the elastomer, and $e$ is the gap thickness. However, for certain functional liquids (e.g., sodium dodecyl sulfate solution [51–53], magnetic fluids [54, 55], and ionic liquids [56, 57]), the wedged films between the two confined surfaces are extremely...
stable and present a lubricated regime even when $S < 0$, because additional physical or chemical forces are generated, thereby supporting the normal load and eliminating dewetting.

2.2 Sliding on elastomer after dewetting

After dewetting, shear sliding in the compliant contacts produces dry frictional effects at a low sliding velocity; these are then transferred to a lubrication regime at high velocities, allowing the transition of forced wetting in the contact area [25, 58]. Martin et al. [25] were the first to focus on such complicated “triboactive” sliding interfaces. They suggested that three friction state regimes (separated by the two critical velocities $U_{c1}$ and $U_{c2}$) configure the sliding process from dry to lubricated (Fig. 1(c)) [25, 58].

2.2.1 Dry-contact regime

At low velocities of $U < U_{c1}$, the soft compliant contact of the elastomer against the substrate remains dry, though the contact area deforms under shear motion. Such dry contact may produce two typical friction behaviors (i.e., Schallamach waves and stick–slip instabilities), even in the presence of liquid, similar to compliant contacts exposed to air [28, 60]. Consequently, a threshold velocity $v_m$ that corresponds to the maximum shear stress of the elastomer sliding in air must be introduced to elucidate the friction characteristics [58]. When $U < v_m$, the Schallamach waves dominate the compliant sliding (for relatively hard elastomers, this becomes a steady smooth sliding regime); meanwhile, when $v_m < U < U_{c1}$, sliding is configured in the instable stick–slip regime.

In contrast to dry sliding in air, Schallamach waves are wet (the rim is filled with liquid); meanwhile, for the stick–slip regime, the slip phase is wet, but the stick phase becomes dry through dewetting [58]. The contact interface is periodically wetted or lubricated by liquids, though the apparent friction force is governed by the percentage of dry area (in a single period of “wet” Schallamach waves or “wet” stick–slip) [61]. Consequently, the lubrication regime of such sliding cannot be simply defined from the traditional tribology viewpoint. However, for a sufficiently hard elastomer, the sliding is steady smooth and can be treated under the “dry friction” regime because a constant dry contact interface is maintained, with no liquid passing through.

2.2.2 Semi-lubricated regime

At the intermediate velocities of $U_{c1} < U < U_{c2}$, the contact interface is partly invaded by the liquid film, where the dry area is restricted to two small dry patches (known as the mixed lubrication regime). This is accompanied by a sizeable friction reduction at the contact interface. Deleau et al. [61] have treated this lubrication mode as a mixed lubrication regime close to fluid lubrication. During sliding, the apparent friction force decreased significantly as the liquid significantly occupied the contact, indicating dry area dependence [62, 63].

2.2.3 Fluid lubrication regime

For a relatively high velocity, $U > U_{c2}$, the contact is fully occupied by the liquid film (forced wetting) with no dry spots; this falls under the full fluid lubrication regime (i.e., the HD lubrication (under a low contact pressure) or elastic-hydrodynamic (EHD) lubrication (under a high contact pressure)). It has been shown that for a low $U$, a sphere elastomer deformed by a tilted planar surface (Fig. 1(c)) [25] and its tilt angle $\theta$ can be predicted using the Hertz contact radius $a$ and film thickness $e$ (Fig. 1(d)). However, if the sliding velocity is sufficiently high, constriction will occur at the rear end of the contact area [64], and the classical horseshoe effect arises (Fig. 1(f)) [59, 65, 66]. This phenomenon has been extensively investigated [67–70].

In fact, the nature of $U_{c1}$ and $U_{c2}$ is a conflict between forced wetting and dewetting [25, 71], independent of the size of the original contact. $U_{c1}$ and $U_{c2}$ can be simply predicted as Eq. (2) [25, 58]:

$$U_{c1} \propto U_{c2} \propto \frac{|S|}{\eta \left(\frac{S}{ER}\right)^{1/3}}$$  \hspace{1cm} (2)

where $R$ is the radius of curvature of the elastomer. The contact remains dry when $v_d$ exceeds $U$, whereas lubrication occurs in the opposite case. A semi-lubricated contact is used when dewetting dominates the rear but is weak at the entry (i.e., $v_d (e_{\text{out}}) > U$ and $v_d (e_{\text{in}}) < U$) (Fig. 1(c)).
3 Effects of surface texture on the wet sliding of soft elastomer

3.1 Friction behaviors of dimple-patterned surfaces

Surface texturing represents one of the most effective methods for modifying material frictional properties; it has garnered significant attention over the past few decades [6, 21, 24, 72, 73]. The typical design objects and application fields of textures include the hard material surfaces of mechanical components (e.g., metal and ceramic), where the focus is on reducing surficial friction and wear and improving lubrication. This topic has been widely investigated and comprehensively discussed [13, 15, 18, 20, 73, 74]. Herein, we restrict our focus to the effect of surface texture on soft elastomer surfaces during wet sliding. Compared with hard surfaces, the easy deformation of soft elastomer surfaces complicates the texture functions. For several conventional designs, the textures exert an anti-friction effect on the soft elastomer surface during wet sliding. However, recent findings have shown that some biological textures (e.g., polygonal patterns on amphibian toe pads) do the opposite, increasing friction on the wet sliding of the soft interface [32, 34, 75]. This suggests that surface texturing can reversibly modify the wet friction behavior of soft surfaces, depending on the configuration design. Current research pertaining to the sliding friction properties of textured soft surfaces and their underlying mechanisms under wet conditions are discussed and systematically summarized below.

3.1.1 Design of surface textures for reducing friction force

Similar to their effects on hard surfaces, textures can reduce the friction of soft surfaces; this facilitates a wide range of applications, such as wipers, artificial joints, and contact lenses. The present configurations of textures on soft surfaces are diverse, including dimples [23, 76], pillars [39, 77, 78], channels [8], and ridges [27] (Fig. 2); their bulk materials are primarily polymers, including polydimethylsiloxane (PDMS) [29, 79], polyvinylsiloxane (PVS) [30], and ultra-high molecular weight polyethylene (UHMWPE) [80, 81]. Numerous tribology studies indicate that dimples are the most typical texture design for friction reduction, and they are more effective when sliding occurs under a lubricant [7, 24, 73]. The friction behaviors of dimples decorated on soft surfaces under wet sliding have been extensively investigated and are summarized in this section.

Wet sliding on a textured surface also conforms to the fundamental laws of lubrication for soft flat control [82]; this, along with the surface wettability and geometrical parameter designs, allows the texture to exhibit diversified performances at the “triboactive” interface. In general, the wet friction force trend on a textured surface with respect to sliding velocity resembles that of flat control (i.e., the friction force decreases under increasing velocity) [76, 83]. In the dry-contact regime, during the initial sliding, the introduction of textures produces a significant friction decrease, similar to the case of air exposure [27, 28]. Kasem et al. [30] employed this to reduce the resistance of a rubber plunger sliding against a barrel (Fig. 3(a)). When sliding under the semi-lubricated regime, the performance of dimple textures is volatile and complicated; textures with the appropriate geometrical parameters can positively contribute to friction force reduction on the surfaces, whereas inappropriate ones have a negative effect (Fig. 3(b)) [29, 76]. For fluid lubrication under high sliding velocities, the dimple textures do not significantly affect the sliding of the soft surface because the friction force between the structured surface and flat control is almost indistinguishable (Fig. 3(b)) [29]. However, based on the studies pertaining to hard textured surfaces [15, 18, 20], the following two functions of textures can be reasonably imposed on soft surfaces: (1) the reserve effect of dimples for lubricant, also known as the second lubrication [14]; (2) the advanced ability to enhance the bearing capacity [18, 84], which is a meaningful parameter for the motion of mechanical pairs.

Huang et al. [29] comparatively investigated the features of wet sliding on textured surfaces and flat control by considering the surface wettability; the friction coefficient results were clearly divided into two regions: hydrophilic and hydrophobic (Fig. 3(c)). As expected, the hydrophilic contact improved
lubrication, as reflected by the friction coefficients a few orders of magnitude lower. A high degree of wettability ensures strong adhesion between the soft surface and lubricant (i.e., a small value of $|S| \leq 5$); this facilitates the transformation from dry contact to semi-lubrication or from semi-lubrication to HD/EHD lubrication (Fig. 1(c)). Furthermore, the effects of dimple textures on wet sliding soft surfaces (to achieve friction) depend on their geometrical parameter design, both in hydrophilic and hydrophobic cases.
To date, the influences of geometric parameters (e.g., the depth, diameter, and area density) of textures on wet sliding have been widely investigated and are well-understood [29, 76, 80, 85]. For example, Figs. 3(d)–3(g) present a summary of the previous investigations, indicating the advantages of shallow dimple construction for sliding. The optimal diameter can be found from the individual operating conditions, and placing more textures in contact results in higher efficiency. In general, the design of dimples has been demonstrated as an effective approach for decreasing friction resistance in the wet sliding of soft surfaces; however, the optimization of geometric parameters is complex and requires various factors to be considered, including the load, Young’s modulus of materials, sliding velocity, and the coupling effects of parameters [20, 22, 86]. Meanwhile, dimple textures combined with certain inappropriate parameters can hinder the friction reduction (Fig. 3(g)); this primarily occurs in the semi-lubrication regime [29, 76]. Several assumptions regarding the mechanisms underlying the positive and negative roles of dimple textures are introduced and discussed in the following section.

3.1.2 Mechanisms of dimple for wet frictions under different lubrication regimes

In the dry contact regime, the friction force of wet sliding is primarily provided by the dry contact, even though it is surrounded by the lubricant. Consequently, the roles of texture on the wet interface may adhere to the principles of dry sliding upon exposure to air. The possible mechanisms of friction reduction are as follows (Fig. 4(a)):

1) Decreased contact area of textured surface. It has been previously reported that the energy required to slide a soft polymer over a substrate is primarily employed to dissociate adhesive molecular bonds in the interface contact (known as adhesive friction) [89–91]. The reduced adhesive area of molecule bonding results in a low friction [27, 28] and weakens the unstable sliding (stick–slip or Schallamach waves) [26, 28] for dry contacts, even when a lubricant is used.

2) Lubrication of residual lubricant stored by dimples. The dewetting (during sliding) of dry contacts depends strongly on the time of film collapse and draining [47, 48, 92]. The lubricant that fails to escape

Fig. 4 (a) Dimples for wet friction on soft surface. (b, c, e) Deformation of dimple-patterned surfaces in the EHD regime. (d) Obstruction effect of dimples for lubricant propagation. Reproduced with permission from Ref. [87] for (b), Elsevier Ltd. 2017; Ref. [88] for (c), © Elsevier Ltd. 2016; Ref. [29] for (d), © Elsevier Ltd. 2012; and Ref. [84] for (e), © Society of Tribologists and Lubrication Engineers 2010.
from the contact region (liquid rim of Schallamach waves or wet slip phase) [93, 94] is captured and stored by dimples. Under shear sliding with a normal load, the stored liquid is extracted to the interface by the deformation of the near-surface layer, thereby eroding the dry region of contact and forming a lubricant for elastomer sliding.

In the semi-lubrication regime, dry patches and a continuous lubricated film (Fig. 1(c)) coexist in compliant contact during wet sliding. This allows dimples to perform multiple functions toward the sliding behavior of the soft surface (Figs. 3(b), 3(c), and 3(h)). For the dry patches, the dimples still perform similarly to the dry-contact regime mentioned above. However, for the lubricated contact region, the function of the dimple array remains unclear, because two conflicting effects have been observed on the interfacial sliding friction behavior. First, convergent dimples can produce numerous micro-HD pressure points; these lift the counter surface, increase the film thickness, and separate the contact, thereby shifting the mixed lubrication to the HD/EHD regime [30]. Moreover, the round edge of the dimple can hinder the movement of the lubricant via the drag forces of surface tension (Fig. 4(d)) [95]. Huang et al. [29] defined the combination of micro-dimple storage and obstruction as the lubricant retaining effect. Second, surface texturing via dimples can be regarded as a contributor to surface roughness; consequently, a local concentration of interfacial contact stress can be easily induced, which may prevent a continuous lubrication film from being formed [76, 96], thereby resulting in high friction forces. The general performance of dimples is governed by the competition between their negative and positive effects. If improper design parameters or extremely heavy loads are used, the negative role of dimples can be amplified, which may increase friction relative to the flat control (Figs. 3(b), 3(c), and 3(e)).

Under the HD/EHD regime, the friction force strongly depends on the internal friction of the lubricant rather than surface textures. Surficial dimples significantly intensify the HD pressure [13, 97], thereby affording a higher bearing capacity to the lubricant film [98–100]. However, for a soft material surface, the enhanced bearing capacity from the dimples imposes a self-adaption effect: variation in the micro-HD pressure coupled with deformation of the dimple-patterned surfaces (Figs. 4(b), 4(c), and 4(e)) [88, 101]. Several recent studies have shown the HD effect of dimple-patterned elastomers, revealing the underlying mechanisms via experiments and theories [84, 87, 88, 101, 102].

3.2 Design of surface textures for increasing friction during wet sliding

The regulation of interfacial friction by surface textures also includes an increase in the friction force. Although the relatively high friction force produced by an array of dimples is feasible on a soft surface, such designs are not suitable for efficiently promoting frictional resistance during wet sliding. Nature offers excellent examples of surface textures exhibiting high frictional attachments under wet conditions. Certain amphibians (e.g., tree frogs [103–105], newts [33, 78], and torrent frogs [106]) manage wet slippery surfaces using their toe pads, which feature topographical designs of polygonal pillar arrays separated by narrow channels. The biological polygonal textures of different species vary slightly: regular hexagonal or irregular polygons in terms of shape, and diameters of 10–30 μm in terms of size (Figs. 5(a)–5(f)) [34]. Moreover, according to the magnified nanoscale images of toe pads, the top of the polygonal columnar texture is not smooth but features a dense array of nanostructures. However, the effects (and extent thereof) of such nano-decorations on wet friction are yet to be elucidated. In this section, we focus on the facilitation of micro-polygonal textures for the increase of wet friction from biological toe pad testing to biomimetics.

3.2.1 Research on biological epidermal textures

Federle et al. [32] systematically investigated the attachment properties of the textured epidermises of tree frog toe pads on wet slippery glass. Their images of the interference reflection showed that most hexagonal textures on the pad epidermis were visibly dark regions, indicating a nanoscale film having a thickness ranging from 0 to 35 nm at the contact interface (Figs. 5(g)–5(j)). This implies that boundary friction dominated the wet contacts between the pads and glasses when shear motion was applied, producing a high interfacial friction force. The underlying
principle was that the design of hexagonal textures allowed redundant fluid to be expelled from the contact area through the networking channels, to produce close contacts (referred to as the draining effect) [107, 108]. Moreover, the presence of grooves can facilitate the increase in friction by hindering the peeling or breaking of two components in contact during dry sliding (i.e., when dewetting occurs, Fig. 1(c)),

Fig. 5  (a) Tree frog and (b) its toe pad, with (c) hexagonal epithelial cells; (d) newt and (e) its toe pad, with (f) polygonal epithelial cells; (g) interference image of a tree frog toe pad in contact with glass; (h) thickness of fluid film along the white arrow in (g); (i) frequency of fluid film thickness, as measured between the tree frog hexagonal cells and glass; (j) friction force during tree-frog sliding experiment; (k) box plots of tree-frog toe-pad shear stress at transition from rest to sliding. Reproduced with permission from Ref. [32] for tree-frog images (a–c) and (g–k), © The Royal Society 2006; and Ref. [78] for newt images (d–f), © IOP Publishing Ltd. 2013.
owing to the suppression of crack propagation at the edges [109] (which is similar to the contact–splitting effect for adhesion in pull-off motion) [110].

3.2.2 Further bionic explorations of polygonal textures

The high wet friction force of polygonal pillars has been conformed in biological organisms; however, further explorations of that texture (to obtain rigorous experimental evidence) are difficult to conduct on the epidermis. Therefore, many researchers have continued to perform investigations using artificial mimics of polymer surfaces. Earlier studies by Varenberg and Gob [111] indicated that the friction force of a PVS surface with hexagonal pillars increased by a factor of more than five compared with a smooth surface when sliding was performed using mineral oil as a lubricant (Figs. 6(a) and 6(b)). The hexagonal textures functioned as friction-oriented features, which prevented hydroplaning on smooth surfaces during wet sliding via the draining effect (the oil was hydrophilic to PVS, and a continuous film was formed during sliding). The extent of increased

Fig. 6  (a) Texture of hexagonal pillars; (b) friction of smooth and hexagonal pillar surfaces in the presence of oil; (c) wet friction force of flat and hexagonal pillar surfaces with respect to sliding velocity; (d) friction behavior of flat and hydrophilic hexagonal pillars with water; (e) effect of hexagonal pillar height on its wet friction force; (f) microscopic image of the hexagonal pillar surface during wet sliding. Reproduced with permission from Ref. [111] for (a, b), © WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim 2009; Ref. [78] for (c), © IOP Publishing Ltd. 2013; and Ref. [107] for (d–f), © The Materials Research Society 2011.
friction on the surface texture depended significantly on its dimensions, and different cross-sections of the channels resulted in varying draining rates. Hence, the benefits of textured surfaces for friction depend significantly on the geometry of the surface design. Experiments by Xie et al. [112] have shown that the factors governing the overall performance of hexagonal pillars are aspect ratios of the geometry (e.g., the width-to-length (W/L), height-to-length (H/L), or height-to-width (H/W) ratios) rather than a single factor (e.g., the width (W), length (L), or height (H)). Relatively high values of H/L or H/W are advantageous to increasing friction, because they allow the pillar texture to bend easily during lateral displacement, which nullifies the surface function of draining.

Huang and Wang [78] experimentally evaluated the differences between round and hexagonal designs for wet friction; they reported that hexagonal pillars can yield higher pattern densities, resulting in more efficient draining and a higher energy dissipation when sliding over discontinuous channels (Fig. 6(c)). By considering wetting as an important factor in interfacial friction, Drotlef et al. [113] investigated the friction behavior of plasma-treated hexagonal pillars and untreated ones, where the lubricated fluid layers were hydrophobic and hydrophilic. They confirmed that the surface texture improved the frictional force only when a wetting fluid was present, and a more prominent increase was identified for the short pillars (Figs. 6(d) and 6(e)). By contrast, the hydrophobic textured surfaces produced a significantly lower friction than the flat surfaces, similar to the dimples.

In nature, the performance of hexagonal pillars in wet friction is also governed by the physical principle of wedged film dewetting. As shown in Figs. 1(b) and 1(c), the dry contact of a boundary friction regime is likely to occur under interfacial sliding in the presence of a liquid if $S < 0$ [25]. For the hydrophobic wetting case, high values of $|S|$ ($S < 0$) imply that a high $U_c$ is configured for the semi-lubrication regime in lubricated sliding (based on Eq. (2)). Consequently, a continuous film between the elastomer contact and substrate is difficult to achieve at low sliding velocities; a dry contact surrounded by the lubricant represents the major form in wet friction. This is reflected by the similar friction values measured in the presence or absence of a fluid, indicating that the non-wetting liquid was immediately displaced from the contact area (i.e., instantaneous dewetting during sliding) (Fig. 6(f)) [113]. As presented in Section 3.1.2, the decreased contact area of the textured surface to the substrate weakened the dry friction force significantly, compared with the smooth surface.

However, for the hydrophilic surface where the wetting-liquid was present, the value of $|S|$ ($S < 0$) was extremely low, resulting in an extremely low $U_c$. The semi-lubrication regime or HD/EHD consequently dominated the wet sliding of the elastomer surface (even at an extremely low sliding velocity), where the thin liquid film invaded and separated the interfacial contact, thereby allowing continuous lubrication (i.e., hydroplaning). Therefore, for the continuous smooth surface, no valid dry contact could be obtained, which resulted in lubricated friction; however, for the textured surface, the configuration of hexagonal pillars extruded the lubricant out through channels and caused dry friction, accompanied by peeling resistance and energy dissipation. Hence, the hexagonal pillars indicated a higher friction force than the smooth surface only during hydrophilic sliding with a wetting liquid, as reported by Drotlef et al. [113].

The advantage of hexagonal pillars for producing high friction (as compared with smooth surfaces) is also reflected in the hydrophobic contacts when the sliding velocity is sufficiently high (i.e., a continuous lubricated film is achieved on flat soft surfaces (Fig. 6(d), see the paper by Huang and Wang [78])). Furthermore, these assumptions apply to the total wetting contacts (i.e., the contact angle of the lubricant is zero) of amphibians, where the continuous lubricant film is always present, based on the fact that amphibians have high frictional abilities [32, 114, 115] (their textured epidermises are completely wetted with water [35, 116]).

3.2.3 Modified hexagonal texture design for better frictional performances

After gaining a comprehensive understanding of the effect of hexagonal pillars on wet sliding, several researchers modified and optimized the designs of pillar texture to further promote the interfacial friction force; these include pillar tip, geometrical shape,
and bulk structure improvements. Such design improvements depend on the prototypical features of biological morphology and aim to produce an artificial surface that closely mimics the organism’s epidermis.

We have reported on hexagonal micropillars with smaller bulges on the top surface; these were fabricated by combining hemispheric crater arrays on a wafer and applying conventional photolithography (Fig. 7(a)) [96]. The array of top bulges accelerates the breaking of the continuous lubricant film of wet contacts (in the hydrophilic case) via stress concentration to enhance the dewatering of hexagonal channels, producing a higher sliding friction than the normal case (Fig. 7(b)). Zhang et al. [117] designed hexagonal pillars with an array of finer cavities on the top (Fig. 7(c)), and an additional suction effect was employed on the substrate of such two-level textures after the interfacial lubricant in contact was drained via the hexagonal channels. This significantly increased the wet friction force under shearing motions (Fig. 7(d)). Recently, the size of the top sucker texture has been further extended to the nanoscale (referred to as nanopits, as shown in Fig. 7(g)) [118], and the sucker shape has been modified to form octopus-like cups [44], thereby achieving reliable high frictional contacts even under flowing water conditions. Another method to improve the design of the hexagonal texture is to embed relatively hard nanopillars aligned in a micropillar bulk (Figs. 7(e) and 7(f)), as reported by Xue et al. [119]. The embedded nanopillars increase the friction force of the hexagonal pillars by shifting the stress maximum from the edge of the contact interface to the top area of a row of nanopillars near the micropillar perimeter and restraining the crack propagation caused by the peeling.

3.2.4 Anisotropic frictions of hexagonal textures

From the perspective of surface design in engineering applications, the intelligent control of surficial friction resulting from wet sliding remains appealing to scientists. To achieve hexagonal pillar textures that prevent hydroplaning, two representative modes of sliding are invoked: corner sliding (sliding along the hexagon side) and side-sliding (sliding perpendicular to the hexagon side). This indicates the anisotropic identity of the texture along the shear direction, which results in the orientation dependence of the friction force. Chen et al. [120] reported that the array of hexagonal pillars exhibited higher friction in the corner direction than in the side one, and the smaller the corner angle, the more significant the distinction is (Figs. 7(j), 7(k), and 7(l)). Images of sliding (Fig. 7(i)) show that the liquid in the corner sliding flowed smoothly to the hexagon angle and then split into a two-way flow through the tilt channels; however, during side sliding, the liquid converged in channels adjacent to the sliding side of the patterns and were extruded, causing the liquid to be flushed into the contact interface; this may have contributed to the friction difference. However, Iturri et al. [121] reported that hexagonal pillars exhibited higher friction along the side sliding direction, after considering the hydrophilic case and pillar height (Figs. 7(h) and 7(i)); the elongated pillars exhibited an even higher friction force than the regular ones. Both the low bending stiffness of the pillars for liquid drainage and the high edge density per unit length of patterns for arresting cracks in the sliding direction contributed to the increased friction. This hypothesis was confirmed from the micro sliding friction maps of the atomic force microscope probe and the high sliding angle of the patterned surfaces during the wet tilting stages (Fig. 7(k)).

Although controversial, the texture design of hexagonal pillars is generally accepted to enable modulation (i.e., not only a mere increase of the friction force) under wet soft sliding. The difference in the present experimental results is most likely attributable to the varying texture geometrical parameters or experimental conditions, such as pillar height, sliding velocity, and lubricant.

3.2.5 Texture of two-phase periodic structures (TPPS) for increasing wet friction

Recently, Moyle et al. [122] proposed a novel texture design known as TPPS, which increases friction on the soft surface for sliding under an EHD regime. In contrast to the draining effect of hexagonal textures, the key role of TPPS in increasing friction is attributed to the energy dissipation (results from periodic variations in the modulus) instead of the occurrence of a dry contact via the breaking of the lubricant film. Such a strategy appears interesting; therefore, a brief review is provided herein. As shown in Fig. 8,
Fig. 7  (a) Texture of hexagonal patterns studded with bulges and (b) their surficial wet friction force. (c) Hierarchical hexagonal pillars with an array of concave tops and (d) their surficial wet shear stresses. (e) Composite hexagonal pillars with nanopillars embedded in bulk and (f) their surficial friction forces. (g) Composite pillars with nanoconcave tops. (h, i) Friction behavior for regular and elongated hexagonal pillars in corner and side sliding. (j–l) Drainage and friction behaviors of various hexagonal pillars in corner and side sliding. Reproduced with permission from Ref. [96] for (a, b), © American Vacuum Society 2015; Ref. [117] for (c, d), © The Authors 2020; Ref. [119] for (e, f), © American Chemical Society 2017; Ref. [118] for (g), © American Chemical Society 2020; Ref. [121] for (h, i), © WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim 2015; and Ref. [120] for (j–l), © American Chemical Society 2015.
compared with the two smooth controls (soft or stiff), the friction behavior measured for the TPPS fluctuates significantly. It varies periodically based on the period of the sample surface texture, and it exhibits a higher average force value. In the microscopic image of wet sliding, the periodic frictional fluctuation is accompanied by changes in the contact region, indicating an abrupt, rapid, and periodically radial lubricant flow in the contact region. This suggests that the energy dissipated via an abrupt local transition in the compliant surface as the modulus changed contributed to the increased friction during wet sliding, and that the energy loss was likely dissipated via fluid movement.

Furthermore, the increased friction might be caused by storage and the irreversible release of energy from the in-plane periodic deformation of the TPPS at the low- and high-modulus interfaces. This assumption was verified by using numerical results from the finite element simulation. To summarize, Moyle et al. [122] present a comprehensive discussion of the TPPS, providing a new strategy for design textures that achieve strong friction under lubricated sliding conditions.

4 Summary and perspectives

Although surface texturing was initially proven effective for improving the tribological properties of mechanical components [7], texture research is still in progress; new properties have been investigated in recent years, including surface wettability [123] and bio-mimic adhesion [124, 125]. This review focused on the current findings on the frictional modulation of texturing on soft surfaces under wet sliding conditions. Two representative types of texturing, dimples (common design applied for friction reduction) and polygonal pillars (bioinspired design from amphibian toe pads), were introduced. The interfacial force of friction on soft surfaces can be either reduced or amplified on soft materials, and the behaviors and underlying mechanisms were discussed and analyzed according to the physical fundamentals of wet sliding. In essence, the textures’ different abilities to achieve interfacial sliding were attributable to their inverse design orientations to liquids; in this design, the polygonal pillars separated through channels were “open” to liquids, whereas the discrete dimples were “closed” to liquids [126]. It was suggested that the surface-texture-induced decrease in contact area, second lubrication, micro-dynamic pressure, draining effect, and so on imposed significant effects. Table 1 provides a brief summary of the results.

The widespread and popular use of soft materials from daily life in industry offers broad frictional application prospects for surface texturing. Several examples are shown in Fig. 9. The potential applications of texture in friction reduction include contact lenses, windscreen wipers, cartilage, capsule endoscopy, and lip seals. These soft surfaces can be decorated by arrays of discontinuous dimples, which can improve the motion smoothness between two contact surfaces in wet cases by decreasing friction resistance and improving lubrication between, e.g., eyelids and contact lenses, capsules and human tissues, and lip seals and shafts. High friction forces from the wet sliding of soft surfaces are in high demand in many applications, including wearable devices (e.g., wound dressing and signal monitoring) [44], wet grasps [117], intelligent robots (e.g., wet transporting and wall-climbing robots) [36], and tires [41]. The design of polygonal pillars is effective for restraining surface hydroplaning and enhancing friction drag on soft surfaces, and the feasibility of their application has been well confirmed (e.g., texturing on skin patches [44] and surgical clips [120]).

Research pertaining to the friction modulation of textures for soft surfaces in wet sliding has progressed significantly. However, the study presented herein is still in its development stage. Challenges remain
regarding the extension of the soft texture mechanism to practical applications. For example, the current theories for texture friction (pillars and dimples) were proposed based on their respective apparent experimental behaviors, which exhibit disunity; however, for textures, concave and convex configurations typically coexist on the same surface, suggesting possible intrinsic links between the sliding performances of pillars and dimples. Consequently, a grand unified theory is necessary to summarize and explain the mechanisms of various textures for interfacial friction; furthermore, surface roughness should be considered because most surfaces are not smooth. Moreover, information regarding the principle of texture design for soft wet surface sliding is insufficient. For textured surfaces to function as intended, structure optimization involving the area density, aspect ratio, size, and spacing must be simultaneously performed, depending on the surface wetting ability, sliding velocity, normal load, elasticity, materials, etc. This is not a simple task, and a convenient array of “design maps” guides is desirable to reduce the design period in practical applications. In terms of texture fabrication, extensive investigations of textures and the continuous discoveries of novel
Textures from nature have shown that textures exhibiting details such as anisotropic shapes, hierarchical designs, or multiscale (from nano to macro) features constitute research targets for tribological applications. However, these diverse shapes pose a challenge to texture fabrication, particularly in mass industrial production, though some smart methods (e.g., multistep template molding, dip transfer method, particle-assisted replication, and inclined reactive ion etching) have been developed in experimental studies [42]. Furthermore, the large area required to fabricate textures on the irregular surfaces of various materials must be addressed in practical applications. To summarize, the regulation or control of friction behaviors on wet soft surfaces using texture design is an interesting topic that should be further investigated.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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