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Contact Friction Regulation of the UV Laser Textured PVA Hydrogel and Titanium Alloy Interface

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ABSTRACT: The soft, hydrophilic and smooth surface of hydrogel displays extremely complex friction behavior. In this work, the ultraviolet laser post-processing created PVA hydrogel surface textures is found to be a one-step effective way for the contact friction regulation at the hydrogel-titanium alloy interface. Micro-grooves with various spacings and depths are fabricated by adjusting the laser scanline interval, laser energy density and the scanning times. Friction torques are measured by a strain-controlled parallel-plate rheometer to characterize frictional behaviors of micro-grooves. At the sliding velocity range of $0.085\text{mm/s} < v < 2.3\text{mm/s}$, the effect of interlocking and ploughing force are the dominant origins of friction. Frictional stress increases with the decrease of the micro-groove spacing, but not with the increase of the micro-groove depth, which indicates that frictional stress doesn't simply increase with an increase of hydrogel's roughness. As the velocity increases from 2.3mm/s to 100mm/s , the surface wettability of textured hydrogel plays an important role in regulating friction. Both smooth hydrogel and laser textured hydrogels show stick-slip phenomenon which occurs in the same velocity range. These results take us a step closer to deriving a more effective, accurate, and dependable guideline for designing laser-textured surface grooves for sliding friction control of hydrogel applications.

Keywords: frictional behaviors, micro-groove, surface wettability, stick-slip phenomenon

Graphic abstract

1. Introduction

Hydrogels, as a kind of soft materials with main component of water, have been getting more and more applications in the fields of soft robots [1,2], intelligent actuators [3-5], issue engineering [6,7] and flexible electronic devices[7,8] by strong plasticity, good elasticity and biocompatibility. The friction contact of hydrogels plays an important role in some mechanical unit structures of soft robot and intelligent actuator [9] to achieve special designed functions, such as hydrogel finger grasping ball [10], soft robot walking [11], hydrogel bionic joint contact [12] and so on. Therefore, the response of hydrogels to friction contact is crucial for the operation accuracy of intelligent mechanical unit structures which is directly related to the failure mechanism of tasks [13]. The strong adhesion and super-slip surface properties of hydrogels have attracted great interest of research. According to Hailong Fan et al. [14], a novel hydrogel for instant adhesion and reversibility (50 times) with strong adhesion strength (180 kPa), hydrophobic, positively charged in water is designed and synthesized by cationic and aromatic monomers, which can firmly adhere to diverse surfaces through interfacial electrostatic and hydrophobic interactions. Super-slip surface is achieved by the brush-like structure [15-17] of articular cartilage, which has attracted great attention of scientists to investigate the friction behaviors on molecular brush of hydrogels [18-22]. Uri Raviv et al. [20] have suggested that in the water environment, the interaction of polyelectrolyte brush and hydrophobic molecular brush produces the long-range osmotic repulsion force and short-range space repulsion force between the direct contact interfaces, which makes the shear force lower than the detection limit ($\pm 20\text{-}30\text{nN}$).

An attractive idea from engineering application scenario is that in addition to the tribological nature caused by the chemical structure of hydrogel itself, can the friction behavior of hydrogel against solid be regulated by the post-processing created surface textures? The friction behavior between hydrogels and solid surfaces in a water environment does not conform to the Amontons-Coulombs' laws that commonly used for two solid surfaces [23], but mainly depends on its own chemical structure relative to the surface properties of substrates and the test environment. Like the two solid surfaces scenario, surface textures have been found to be an important factor in regulation of friction between the hydrogel and the solid interface [24, 25]. Taiki Tominaga et al. [26] have reported the effect of glass surface roughness on the friction of PVA hydrogel-glass interface: If the glass roughness (R_a) is less than 100nm, the friction doesn't change significantly. If the glass roughness R_a increases to 1000nm, the friction force decreases rapidly at $v \approx 10^{-2}\text{m/s}$. However, most of the previous studies are related to the effect of solid surface roughness on the hydrogel friction properties. Although the lubrication mechanisms have been studied among the very rich and complex frictional behaviors of hydrogels [26-31], the laws in the manipulation of friction behavior of hydrogel surface by artificial textures are still unclear due to the lack of proper surface texturing method for the soft hydrogels. Shintaro Yashima et al. [28] have prepared PAAM hydrogels by sand blasting on the glass mold to form various roughness surface, and reported the effect of the roughness of the hydrogel on the friction force. Unfortunately, the mold forming method is effective only for precursor solution with good fluidity and wettability, but for the PVA solution with high viscosity, the surface texture consistency is poor because of insufficient infiltration. Recently, Haoyi Yu et al. [32] have reported the low threshold laser direct writing of PEGda hydrogel by a 535nm green femtosecond laser beam and 2-hydroxyl-2-methyl propofol (HMPP) as the photo-initiator, and the laser prepared surface textures of hydrogel show promising controllability.

In this paper, micro-grooves with different depths and spacings are prepared by the high energy density ultraviolet (UV) laser texturing on the PVA hydrogel surface. Then, the friction law of laser textured hydrogel against titanium alloy surface is characterized and studied. A friction regulation model of the hydrogel micro-grooves is proposed to describe the frictional force at the hydrogel-titanium alloy interface. It is proved that the tribological nature of the hydrogel surface can be easily controlled by the laser post-processing of micro-grooves.

2. Materials and methods

2.1 Friction pair materials

Polyvinyl alcohol (PVA) (polymerization degree: 2600; saponification ratio: 99%) is purchased from Shandong Yousuo Chemical Technology Co., Ltd. The physically crosslinked PVA hydrogel is prepared by a freeze-thaw method from an aqueous 12%wt. Polymer solution is prepared by heating a mixture of PVA in the aqueous medium for 1 h at 90°C. After heating, the PVA solution is cast into self-made mold with a cylindrical acrylic space (diameter: 20mm, depth: 3mm) for accommodating the solution, and the solution in the mold is subjected to 3 cycles of freezing at -40°C for 16h and thawing at room temperature for 8h. Subsequently, the hydrogel is immersed in a large amount of distilled water for one week.

Disc-shaped TC4 titanium alloy (diameter: 40mm) is purchased from Baoji Boyuanxin Industry and Trade Co., Ltd, and polished with polishing compound (particle size: 2.5μm).

Compressive modulus of the as-prepared hydrogel is measured by the dynamic thermo-mechanical analysis (Q800, TA instruments). The test sample of 20mm diameter and 3mm thickness is compressed with a velocity of 10% thickness per minute. Nonlinear behavior at small deformation in the stress-strain curve is observed typically due to the natural sample depth variation [33]. At a strain of approximately 9%, the obtained stress-strain curve becomes linear and the slope is used to calculate the Young's modulus of hydrogels. The calculated Young's modulus E of the test sample is 638 kPa.

The characteristics of surface morphology of friction pairs are observed by a confocal microscope (OSL4100, OLYMPUS, Japan). Arithmetic mean deviation of surface (S_a), an extension parameter based on R_a , is calculated for three different observation areas (scanning area: 644μm×644μm). S_a refers to the arithmetic mean or geometric mean of the distance between the points on the surface and the central plane in the observation area. Compared with arithmetical mean deviation of the profile (R_a). S_a can better reflect the roughness of a surface. The mathematical expression of S_a is as follows:

$$S_a = \frac{1}{l_x l_y} \int_0^{l_x} \int_0^{l_y} |Z(x, y)| dx dy \quad (1)$$

When l_x and l_y are the distance of the observation area along the X and Y axes respectively, $Z(x, y)$ is the distance from the point on the observed surface with coordinates (x, y) to the central plane.

The static contact angles (SCA) of the samples are measured by a video optic CA instrument (OCA15EC, Dataphysics). Samples are tested using 2μl distilled water and videos of the droplet wetting process are recorded to get the stable time of droplet.

2.2 Laser surface texturing method

The prepared hydrogel samples are irradiated in the air with a nanosecond UV laser (Super Pluse 355-12, Suzhou Yinggu Laser Co., Ltd, China). The laser processing system parameters are summarized in Table 1. Laser energy density, or fluence, is defined as the laser energy per irradiated area, and it is one of the most important laser processing parameters that control the surface morphology [34]. To produce the micro-groove pattern, the laser scanning is performed line-by-line in the x direction and then in the y direction by a X-Y galvo-scanner (Fig.1). The spacing of the micro-groove is controlled by adjusting the scanline interval. The depth of the micro-groove is obtained by adjusting the laser energy density and the counts of scanning. All samples are divided into two groups. Group 1 consists of a series of depth gradient samples: $3\pm0.7\mu\text{m}$ (laser energy densities: $360\text{J}/\text{cm}^2$, scanning times: 1), $15\pm2\mu\text{m}$ (laser energy densities: $510\text{J}/\text{cm}^2$, scanning times: 1) and $30\pm4\mu\text{m}$ (laser energy densities: $510\text{J}/\text{cm}^2$, scanning times: 3) with the same spacing of $100\mu\text{m}$. The textured hydrogel samples are denoted as TH_3/100 (micro-groove depth/spacing in μm), TH_15/100 and TH_30/100, respectively. Group 2 consists of a series of spacing gradient samples: $50\mu\text{m}$, $100\mu\text{m}$ and $200\mu\text{m}$ with the same depth of $15\pm2\mu\text{m}$ by the laser energy density of $510\text{J}/\text{cm}^2$ and scanning times of 1 which are denoted as TH_15/50, TH_15/100 and TH_15/200, respectively.

Table 1 Laser processing parameters of micro-groove array on hydrogel surface.

Laser parameter	Symbol (unit)	Values
Average power	P (W)	12
Wavelength	λ (nm)	355
Pulse duration	τ (ns)	20
Repetition rate	f (kHz)	50
Spot diameter	Φ (μm)	20

Fig.1 Surface micro-grooves of hydrogel prepared by UV laser surface texturing: **a** UV laser scanning platform, **b** The schematic illustration of laser texturing of hydrogel sample

2.3 Surface tribological properties characterization

The friction of PVA gels against titanium alloy substrate in pure water is characterized using a rheometer (HAKKE MARS60, Thermo Fisher Technology Co., Ltd) that operates in a constant compressive strain-controlled shear mode (Fig.2). The disc-shaped hydrogel with a diameter of 20mm and a thickness of 3mm is glued on the same size circular acrylic plate using cyanoacrylate instant adhesive agent (Xi'an Jianghang Rubber Co., Ltd) and the other side of circular acrylic plate is glued on the upper platen of the rheometer using double faced adhesive tape (Shenzhen chuangzaocheng Technology Co., Ltd) in order to keep the rotor of the rheometer clean. The self-made titanium alloy circular flume is glued onto the lower

aluminum plate of the rheometer. After 2ml of pure water is injected into the self-made titanium alloy circular flume, the disc-shaped hydrogel is moved perpendicular to the titanium alloy surface until the load reaches 1.9kPa. The distance between rotor and titanium alloy surface is kept unchanged for 5 minutes to provide a stable contact force.

In order to prevent only shear deformation of hydrogel and no relative sliding at hydrogel-titanium alloy interface during the low-velocity rotation test, pre-rotation test is carried out for 20s at 60rad/min before the formal test. Then the friction torque is measured in the rotation test mode at a set constant angular velocity (ω). The rotation test lasts for 1min, and collects the torque data every 1s. The average value of collected data of the last 20s is adopted as the average torque T . Before the next run, the gel is separated from the substrate for 10min for stress relaxation.

In the self-made friction flume, friction interface is immersed in water and friction is characterized in the velocity range of $0.0085\text{mm/s} \leq v \leq 4700\text{mm/s}$. As the effect of asperities of hydrogel on friction will diminish under a large normal compression,³¹ we confine our study to the condition that the normal pressure (1.9kPa) is very low relative to the modulus (638kPa) of the gel, corresponding to a normal strain at about 0.3%. Although creep occurs during pressure, the diminishing effect of micro-grooves is still very weak.

According to the distribution of frictional stress shown in Fig.2(b), the maximum frictional stress is assumed to occur at the maximum sliding velocity of hydrogel-titanium alloy interface ($v=\omega R$), therefore the maximum frictional stress is calculated as follows [35]:

$$\sigma(\omega R) = \frac{2T(\omega)}{\pi R^3} \quad (2)$$

When $T(\omega)$ is the torque measured by rheometer, ω is the angular velocity of hydrogel.

Fig.2 Frictional test and the distribution of shear stress: **a** The experimental setup of the frictional test, **b** The schematic illustration of the frictional test and the distribution of frictional stress(σ). T : friction torque, ρ : radial distance, σ_ρ : frictional stress at the radial distance of ρ , $\sigma_{\max}$: maximum frictional stress

3. Results and discussion

3.1 Topological structure of laser textured hydrogel

The microscopic surface morphologies of smooth titanium alloy and hydrogel are shown in Fig.3. The polished titanium alloy surface has a small value of S_a by $0.06\mu\text{m}$ and its maximum height drop is about $0.6\mu\text{m}$. The prepared hydrogel surface has a S_a of $0.15\mu\text{m}$, which is rougher than acrylic mold surface (S_a : $0.065\mu\text{m}$). This is caused by two factors: (1) The thermal expansion coefficient of hydrogel is different

from that of mold, which leads to insufficient contact between hydrogel and mold during freeze-thaw process. (2) When the interface between hydrogel solution and acrylic mold wall is treated at -40°C , not all water exists in the hydrogel network structure in the form of bound water. Part of the water exists in the interface between hydrogel and acrylic mold wall, and crystallizes due to low temperature freezing, resulting in uneven concave and convex surface of hydrogel. After freeze-thaw treatment and demoulding of hydrogel, there are 1-5 micron puddles on the surface of hydrogel.

During the laser surface texturing process, the bonded water in the PVA hydrogel is converted into free water due to the destruction of the network structure of the hydrogel in the micro-grooves after etching by laser. This will result in that after progressive scanning in the X direction, part of the laser energy will be absorbed by water during progressive scanning in the Y direction, affecting the consistency of the etched micro-grooves on the surface of the hydrogel in the X scanning direction and in the Y scanning direction.

Fig.3 Surface morphology of smooth surface: **a** Polished titanium alloy, **b** Unprocessed hydrogel, **c** Line profiles of smooth surface

The micro-grooves with different spacings are fabricated by changing the scanning interval with an UV laser with an energy density of $510\text{J}/\text{cm}^2$. When the scanning interval is larger than $50\mu\text{m}$, the fabricated micro-grooves are highly consistent (Fig.4d). When the laser scanning interval is decreased to less than $50\mu\text{m}$, a large amount of water exists in the micro-grooves and absorbs part of the laser energy, leading to a significantly shallower etching depth.

Fig.4 Microscopic surface morphology of the laser textured hydrogels: **a** TH_15/50, **b** TH_15/100 and **c** TH_15/200. **d** Line profiles of the laser ablated micro-grooves with different spacings

Fig.5 Microscopic surface morphology of the laser textured hydrogels: **a** TH_30/100, **b** TH_15/100 and **c** TH_3/100. **d** Line profiles of the laser ablated micro-grooves with different depths

The micro-grooves with different depths are fabricated by changing the laser energy density and scanning times. Due to the laser energy distribution is Gaussian, the light intensity distribution gradually decreases along the radius, resulting in the center area of the spot to reach the PVA ablation energy threshold. This is closely related to the width of micro-grooves. Therefore, when the laser energy density is $360\text{J}/\text{cm}^2$, the micro-groove's width and depth of the sample HT_3/100 are the narrowest (about $13\mu\text{m}$) and the shallowest (about $3\mu\text{m}$) (Fig.5c). When the laser energy density is increased to $510\text{J}/\text{cm}^2$ for sample HT_15/100, the central light intensity is stronger, and micro-grooves with the larger width of about $25\mu\text{m}$ and larger depth of about $15\mu\text{m}$ are achieved (Fig.5b). Different from the laser processing law of solid surfaces, the laser energy density used for texturing the hydrogel surface should not be too large, because excessive heat accumulation either by increasing the laser energy or reducing the scanning velocity on the hydrogel surface will cause the temperature near the laser irradiation area exceeding the phase transition temperature and forming a large pit of a few millimeters in diameter. The elastic modulus of the hydrogel around the pit becomes significantly smaller and its color changes from white to transparent. Thus, the sample HT_30/100 with the largest width of about $35\mu\text{m}$ and depth of about $30\mu\text{m}$ is prepared by another strategy of low energy density + three scanning times in order to effectively reduce the thermal accumulation. With the increase of processing times, the residual water in the first scan path will weaken the further deepening of the hydrogel grooves in the subsequent scanning. Due to the presence of water in the micro-grooves during the second and third scanning, the laser-ablated hydrogels are not conducive to gasification and discharge from the grooves. Some re-solidified hydrogels show clusters of several microns at the bottom of the grooves (Fig.5a).

3.2 The contact friction regulation at the laser textured hydrogel-titanium alloy interface

In order to discuss the contact friction regulation by laser fabricated surface textures, the origins of friction force between the laser textured hydrogel and titanium alloy surfaces must first be defined as a physical model. The schematic origins of friction on the interface between laser textured hydrogel and titanium alloy surfaces are shown in Fig.6. Four factors should be considered on the soft-hard interface in a sliding scenario:

Fig.6 The origins of friction at the laser textured hydrogel-titanium alloy interface

1) Adhesion force (F_A): The frictional resistance caused by adhesion comes from the molecular interaction between hydrogel and the titanium alloy interface. When the relative sliding velocity (v) of the interface is much larger than the characteristic velocity (v_f) [26] that the soft polymer does not have enough time to form a stable adsorption point on the surface of titanium alloy, the adhesion force will completely disappear.

2) Interlocking force (F_I): The interlocking effect is caused by the asperities on the interface of titanium alloy and the laser textured hydrogel surfaces. The interlocking force is mainly affected by the actual contact stress, the size of micro-bulges and micro-grooves, the temporal and spacial interlocking repetitions, and the viscoelasticity of the material.

3) Ploughing force (F_P): The resistance to the elastic deformation of hydrogel is caused by the "ploughing behavior" of the surface asperities of hard titanium alloy on the smooth part of the hydrogel surface. Ploughing force is mainly affected by actual contact stress and viscoelasticity of material.

4) Fluid resistance (F_F): The internal friction of the fluid between the laser textured hydrogel and titanium alloy surfaces dominates the friction at high velocities and makes the kinetic energy of fluid eventually dissipated as heat. The law of fluid resistance follows the law of parallel plate shear flow.

Thus, the origins of friction force (F_f) can be written as:

$$F_f = F_A + F_I + F_P + F_F \quad (3)$$

The three resistant effects of adhesion force (F_A), interlocking force (F_I) and ploughing force (F_P) are all related to the elastic dissipation of hydrogel energy produced by the macroscopic elastic deformation (the shear deformation of the whole hydrogel along the sliding direction) and the microscopic elastic deformation (the deformation of the micro-groove and the smooth surface caused by asperities on the titanium alloy surface) of the hydrogel both of which play an important role in the low velocity region.

The typical σ - t curves of TH_30/100 in stick-slip velocity range is shown in Fig.7. When $v=0.76\sim 21\text{mm/s}$, the stick-slip cycle decreases from about 80s to 3s with the increase of velocity, but when the velocity increases to 62mm/s , the stick-slip cycle increases again to about 70s. In the range of $v=0.76\sim 21\text{mm/s}$, the time required for the accumulation of tangential stress decreases with the increase of the velocity, which makes the hydrogel reach the threshold of destructive adsorption faster. However, when the velocity increases to 62mm/s , only a few low-velocity regions near the center of the hydrogel disc can form stable adsorption points. It takes longer time for the cumulative shear force along the radial direction to reach the threshold.

Fig. 7 σ - t curves of TH_30/100 in stick-slip velocity range

In previous reports [36], no stick-slip phenomenon occurs at the interface between silicon hydrogel and glass surface when the normal stress is lower than 10kPa , whereas stick-slip phenomenon becomes more

and more obvious with the increase of the normal stress value larger than 10kPa. In this study, the stress used is 1.9kPa, but there is still obvious stick-slip phenomenon. This is because both glass and hydrogel in the previous report are hydrophilic materials, which easily forms a hydration layer between the two surfaces. The contact angle (CA) of smooth titanium alloy surface in this study is 95° , which means the titanium alloy surface is easier to separate from water than that of glass. Even in the case of light load, the hydration layer is displaced to form a direct contact. It is worth noted that the stick-slip phenomenon on both the smooth and laser textured hydrogels occurs as the velocity reaches 0.76mm/s, then completely disappears as the velocity is around 100mm/s. This indicates that stick-slip phenomenon is independent of the occurrence of interlocking and ploughing force, but only related to the generation and disappearance of adhesion force between two surfaces.

The friction force change caused by the response behavior of hydrogel surface textures at different velocity can not be explained simply by the traditional Stribeck curve [29]. The stick-slip process at the laser textured hydrogel-titanium alloy interface can be described as follows: Due to the forming of stable adhesion force at static or low velocity status, the rotation of the rheometer only makes the hydrogel present macroscopic elastic shear deformation, and the contact interface does not relatively slip. The tangential stress of the hydrogel is released rapidly when it accumulates enough to destroy the stable adsorption force at the interface, therefore the frictional stress decreases rapidly [36]. The relative sliding velocity is higher than what we originally set and the stable adsorption point cannot be formed. When the relative slip velocity slows down to around v_f , new adsorption points are formed again and the subsequent stick-slip cycle begins.

Fig.8 Frictional stress curves regulated by different spacing micro-grooves: **a** σ - v curves of different spacing micro-grooves and **b** Frictional stress curves at low velocity

The frictional stress curves regulated by different spacing micro-grooves are shown in Fig.8. In the low velocity region $v=0.085\sim 2.3$ mm/s, whether or not the hydrogel surface has micro-groove, adhesion and ploughing force lead to an increase in the frictional stress with the increase of velocity (Fig.8a). The laser textured hydrogels are also affected by interlocking force, which makes the the frictional stresses of laser textured hydrogels is larger than that of smooth hydrogel. The smaller the spacing of micro-grooves, the larger the frictional stress on the surface of hydrogel (Fig.8b). With the increase of velocity and the decrease of spacing of micro-grooves, the interlocking of the micro-grooves and asperitise will happen more frequently and leads to an increase of the frictional stresses (Fig.9a). It can also be seen in Fig.8(b) that the frictional stress at the same velocity increases with the increase of S_a , which is consistent with common belief that “the rougher the surface, the larger the frictional stress”.

Fig.9 Schematic illustration of the friction regulation model of hydrogel micro-grooves: **a** Different spacing micro-grooves, **b** Different depth micro-grooves and **c** Action mechanism of water entrapment

As shown in the Fig.9, laser material removal makes real contact area (S_r) of laser textured hydrogels be smaller than that of smooth hydrogel, which results in a higher real contact stress of laser textured hydrogels under the same normal force ($\sigma_r = F_N / S_r$). As the velocity increases, the smooth hydrogel at lower stress is easier to separate than the laser textured hydrogel. Another factor promoting the separation is the formation of "water entrapment" between smooth hydrogel-titanium alloy interface [28]. The water entrapment can separate the two surfaces and share part of the normal stress (Fig.9c). This results in a smaller hydrogel-titanium alloy direct contact area and a smaller hydrogel-titanium alloy direct contact pressure. When the laser textured surface contacts and extrudes against the titanium alloy surface, the micro-groove acts as a "drainage channel" [28]. The water is discharged out of the interface along the drainage channel and doesn't share the pressure between the two surfaces at low velocity.

When the velocity increases from 2.3 to 100mm/s (Fig.8a), the water entrapment separates a larger area of the smooth hydrogel-titanium alloy interface and shares more pressure, and the frictional stress begins to decrease. Micro-grooves, as the "drainage channels", inhibit the occurrence of continuous water film at the interface during the rotation process, which causes frictional stress of laser textured hydrogels to continue to increase. Although the contact angle of TH_15/50 (CA:0°) is the same as that of TH_15/100 (CA:0°), the stable time of droplet of TH_15/50 (30s) is longer than that of TH_15/100 (17s), indicating that the fluid has weaker ability to diffuse and larger resistance in the micro-grooves of TH_15/50. Thus, the fluid tends to separate TH_15/50 and titanium alloy interface rather than flow in the micro-grooves, which results in a smaller area of direct contact and a slow rising frictional stress. The wettability of TH_15/200 (CA:5.9°) is worse than that of TH_15/50 (CA:0°) and TH_15/100 (CA:0°), and the frictional stress of TH_15/200 has the largest rising trend and slightly exceeds that of TH_15/100 at the peak.

When the velocity reaches about 100mm/s (Fig.8a), the stick-slip phenomenon disappears. A continuous hydration layer is formed between two surfaces, and the frictional stress curves of all the laser textured hydrogel begin to decrease rapidly. However, there is relatively more fluid in TH_15/50-titanium alloy

and smooth hydrogel-titanium alloy interface, and the downward trend of frictional stress is relatively moderate.

Fig.10 Frictional stress curves of different depth micro-grooves: **a** σ - v curves of different depth micro-grooves and **b** Frictional stress curves at low velocity

Fig.10 shows the frictional stress curves of different depth micro-grooves. The largest width and smallest real contact stress of the TH_30/100 micro-groove among TH_3/100, TH_15/100 and TH_30/100 cause the largest real contact stress and produce the largest frictional stress. When the micro-grooves are subjected to the tangential force, a largest deformation quantity is caused in the process of sliding. However, it does not fit the common belief that "the rougher the surface, the larger the frictional stress" in the low velocity region ($v=0.085\sim 2.3$ mm/s), the arithmetic mean deviation of TH_3/100 ($S_a=1.20\mu\text{m}$) is smaller than that of TH_15/100 ($S_a=2.28\mu\text{m}$) but the frictional stress of TH_3/100 is larger. The reason is shown in Fig.9(b), the size (about $0.6\mu\text{m}$) of asperity of titanium alloy is more consistent with the depth of TH_3/100 than that of TH_15/100, forming a stronger interlocking force in TH_3/100-titanium alloy interface [30].

At the velocity range from 2.3 to 100 mm/s, the frictional stress between TH_3/100 and TH_30/100 does not continue to rise. TH_3/100 owns the lowest depth ($3\mu\text{m}$) and a large spacing ($100\mu\text{m}$) of micro-grooves. Thus, there is less spacing of micro-grooves to hold water. More water flows between the TH_3/100-titanium alloy interface than in the micro-grooves, which shares part of contact stress and reduces frictional stress slightly. As the TH_30/100 micro-grooves hold more water to lubricate and form a larger wedge due to the largest deformation quantity, it is easier for the top of micro-grooves to slide away from the asperities of the titanium alloy (Fig.9b). However, with the further increase of velocity, the interlocking, ploughing force and fluid resistance continue to strengthen, resulting in the slight increase of frictional stresses of TH_3/100 and TH_30/100. In this velocity range, the stable time of droplet on the surface of micro-grooves with different depths are TH_3/100(1.8s) > TH_30/100(7s) > TH_15/100(17s), whereas the frictional stress are TH_3/100 < TH_30/100 < TH_15/100. The less stable time, the smaller the frictional stress.

When the velocity reaches about 100 mm/s, the stick-slip phenomenon disappears completely, which is the same as the micro-groove with different spacings. Due to friction interface of TH_3/100 and TH_30/100 has more fluid in the low velocity region, the downward trends are less than that of TH_15/100. S_a of TH_3/100 and smooth hydrogel are the lowest, and they enter fluid lubrication at $v=556$ mm/s. The micro-grooves of TH_30/100, which holds large amounts of water, enter fluid lubrication at $v=1669$ mm/s.

TH_15/100 enters fluid lubrication at $v > 4712\text{mm/s}$. After entering the fluid lubrication, the frictional stress conforms to the shear flow law between parallel plates, and the frictional stress is positively correlated with the shear rate.

Conclusions

Micro-groove textures with different depths and spacings are prepared by the UV laser texturing on the PVA hydrogel surface, and proved to be an effective way for the contact friction regulation of the hydrogel-titanium alloy interface. The laser textured micro-grooves enable the effect of "drainage channel" and interlocking at the hydrogel-titanium alloy friction pair interface, making the frictional stresses of textured hydrogel be always larger than that of smooth hydrogel at various velocity. Both decreasing the spacing of micro-grooves and increasing the sliding velocity can increase the interlocking force. Compared with TH_15/100, TH_3/100 with smaller Sa has a larger interlocking force, which forms a stronger frictional stress.

The frictional stress is affected by the wettability of the hydrogel surface when the sliding velocity is in the range of $2.3\text{mm/s} < v < 100\text{mm/s}$. In a series of micro-groove spacings, with the increase of velocity, the largest contact angle is TH_15/200 (CA:5.9°) which owns the largest rising trend of frictional stress and it exceeds the frictional stress of TH_15/100 (CA:0°) at 62mm/s. In a series of micro-groove depths, the less the stable time of droplet on the laser textured hydrogel surfaces, the smaller the frictional stress. When the sliding velocity exceeds 100mm/s, the polymer can not form a stable adsorption point on the titanium alloy surface, resulting in failure of adhesion force. The stick-slip phenomenon of all hydrogels against titanium alloy is completely disappeared, and the frictional stress begins to decrease.

The results reveal the feasibility of regulating the friction stress of hydrogel-solid interface under low load by laser texturing of micro-groove array with designed depths and spacings, which is of great significance for bioengineering friction applications, such as artificial articular cartilage, muscle and heart valve.

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Ethics declarations

Conflicts of interest

The authors declare that they have no conflicts of interest.

Ethical Approval

All ethical responsibilities were respected by the authors.

Consent to Participate

All authors contribute and participate to work carried out in this paper.