Applied Surface Science 385 (2016) 249–256

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Anti-adhesion effects of liquid-infused textured surfaces on high-temperature stainless steel for soft tissue

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ARTICLE INFO

Article history:
Received 22 February 2016
Received in revised form 5 May 2016
Accepted 20 May 2016
Available online 1 June 2016

Keywords:
Anti-adhesion
Liquid-infused surfaces
Stainless steel
High-temperature
Soft tissue

ABSTRACT

Soft tissue adhesion on the electrosurgical instruments can induce many serious complications, such as failure of hemostasis and damage to the surrounding soft tissue. The soft tissue adhesion is mainly caused by the high temperature on the instrument surface generally made of stainless steel. *Nepenthes* inspired liquid-infused surfaces (LIS), highly promising for anti-adhesion, have attracted considerable interests. In this paper, we investigated the anti-adhesion effects of LIS on high-temperature stainless steel for soft tissue for the first time, aiming to develop a new approach to solve the soft tissue adhesion problem. The textured surface, acting as the holding structures, was fabricated by photolithography-assisted chemical etching. Silicone oil, with good biocompatibility and high-temperature resistance, was chosen as the infused liquid. The adhesion force measurements for soft tissue on the LIS at high temperatures indicated that the soft tissue adhesion force was decreased by approximately 80% at 250 °C. Besides, the cycle tests of soft tissue adhesion force demonstrated the excellent stability of prepared LIS. We anticipate that LIS will be of great promise for practical applications on the electrosurgical instruments.

1. Introduction

Soft tissue adhesion always occurs after surgical treatment, especially electrosurgical soft tissue cutting via monopolar electrode, bipolar forceps, and ultrasonic scalpel [1–3]. These energy-based surgical instruments produce severe temperature rise on the instrument tip as the surgery performs, and the high temperature of the tip can easily char the soft tissue and tear it to adhere on the instrument [4–6]. The adhesion of charred soft tissue on the surgical instrument may result in failure of hemostasis or damage to surrounding soft tissue [2,6], and the soft tissue on the instrument may further obstruct the function execution and induce difficult surgery which may also lead to a potential danger to the patient [7,8]. So, adhesion of the soft tissue on the surgical instrument is a problem that should be thoroughly resolved.

The adhesion arising on the electrosurgical instrument perform unit, which is usually made of metal such as stainless steel, is generally ascribed to be a temperature-induced physical adhesion [5,9]. In order to decrease the adhesion of soft tissue on the electrosurgical instrument surface, several methods including adding agents, spraying cooling water, and making coatings or films on the contact surface of the instrument have been devised [10–19]. Adding agents did not prevent adhesion formation effectively because of short-term residence [2], and spraying cooling water was difficult to control and the energy from the electrosurgical instrument could make the water boil which may burn the surrounding soft tissue [13]. Using coatings or films to construct a physical barrier between the soft tissue and the instrument surface is regarded as a relatively effective method. In general, the coatings or films can be divided into three types: metal coatings [14,15], synthetic polymer films [16,17], and metal-polymer composite coatings [18]. Although metal coatings can reduce the soft tissue adhesion on the electrosurgical instrument surface, the materials of the coatings mainly include noble metals, such as gold and silver, which increase the money cost and make the electrosurgical instrument difficult to be widely used among ordinary people. Synthetic polymer films, mainly including polytetrafluoroethylene (PTFE) films, are adopted because of their low surface energy, and they can reduce the soft tissue adhesion as well. But the synthetic polymer films are not very stable under high temperature, for example, the PTFE films may decompose poisonous gas or particulates at the temperature of above 260 °C [20]. Metal-polymer composite coatings hold the advantages of both the metal coatings and the polymer films, while they collect their disadvantages as well. In addition, these coatings or films are also plagued with fabrication process complexity and easy falling off to become an adhesion growth point.

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http://dx.doi.org/10.1016/j.apsusc.2016.05.110
0169-4332/

Recently, novel slippery anti-adhesion liquid-infused surfaces (LIS), inspired by carnivorous pitcher plant *Nepenthes*, have been fabricated by constructing a liquid/solid composite surface [21,22]. For preparing LIS, surface structure is initially fabricated to firmly hold the liquid in place. The liquid can form a stable barrier between the substrate and the contact object, resulting in a liquid/object interface instead of substrate/object interface [23,24]. Previous studies have demonstrated the marvelous anti-adhesion capacity of the LIS for biofouling [25,26], ice [27–29], frost [30], varieties of other liquids [31–33] and so on. Herein, we investigated the anti-adhesion effects of the LIS for soft tissue at high temperatures for the first time. The stainless steel was textured by photolithography-assisted chemical etching to construct the holding structures. The silicon oil was chosen as the barrier liquid because of its good biocompatibility and high-temperature resistance [34,35]. Finally, the anti-adhesion effects of the prepared LIS for soft tissue were investigated by adhesion force measurements and cycle tests, and the possible anti-adhesion mechanism was also proposed.

2. Experimental details

2.1. Materials

The stainless steel, used as the substrate, was commercially obtained from Hongtu Corporation (Guangzhou, China) and was cut into square pieces (3 cm × 3 cm). The negative photoresist (KMP BN308-450, viscosity 470 ± 30 mPa S) and its stripper in the photolithography experiment were purchased from Kempur Microelectronic Corporation (Beijing, China). The H_3PO_4 (Phosphoric acid), HCl (Hydrochloric acid), and $FeCl_3$ (Ferric chloride) in chemical etching solutions, obtained from Tianjin Chemical Corporation (Tianjin, China), were analytically pure and used as received. The silicone oil with different kinematic viscosities, purchased from Beijing Chemical Works (Beijing, China), was used as the infused liquid. Octadecyltrichlorosilane (OTS) was purchased from Huaxia Reagent (Chengdu, China), as the silane to functionalize the textured surface to promote the spreading and impregnation of the silicone oil. Lean meat of the pig was applied as the soft tissue because of its relatively pure composition and easy manipulation for adhesion force measurement.

2.2. Preparation of textured stainless steel surfaces

Photolithography-assisted chemical etching was employed to fabricate the surface structure on the stainless steel. Fig. 1a shows the schematic of the fabrication process. Before spin-coating of photoresist, the stainless steel was firstly immersed into alkaline solutions (composition: NaOH 50 g L^{-1}, Na_2CO_3 40 g L^{-1}) for 15 min to remove the oil stain. And then, the stainless steel was thoroughly washed by ultrasonic cleaning in the order of deionized water, *n*-hexane, acetone, and ethanol for 10 min, respectively, followed by vacuum drying at 150 °C for 30 min. The negative photoresist was spun onto the stainless steel at the speed of 1500 rpm for 20 s and the photoresist thickness was approximately 10 μm. The stainless steel was placed on the hotplate for prebaking at 120 °C for 3 min. The photolithography was carried out in a contact aligner with UV-light wavelength of 254 nm and light intensity of 13 mW cm^{-2} for 25 s. The structure definition of the mask can be seen in the inset of Fig. 1a. The mask diameter is defined as the diameter of the circular array in the mask film and the mask space is defined as the minimum distance between two neighboring circular masks. A post exposure bake at 120 °C was conducted on the hotplate for 2 min and then the substrate with photoresist was developed in the stripper for 10 min to obtain the photoresist texture. Chemical etching was conducted in a beaker with approximately 500 mL chemical etching solution (composition: $FeCl_3$ 400 g L^{-1}, Phosphoric acid 20 g L^{-1}, Hydrochloric acid 100 g L^{-1}). The etching depth could be controlled by etching time. After chemical etching for a certain time, the stainless steel was took out and washed by deionized water. Stainless steel texture was obtained after the remainder photoresist was all removed by ultrasonic cleaning in acetone for 5 min. Images of 1–3 in Fig. 1b, corresponding to the steps labeled by 1–3 in Fig. 1a, show the morphology change of the stainless steel surface texture.

2.3. Preparation of lubricant-infused anti-adhesion surfaces

To construct a stable solid/liquid composite surface, the substrate must have a high affinity for the liquid. Considering that the silicone oil was chosen as the liquid, the substrate was functionalized with silane to make the surface chemical property match the silicone oil. The stainless steel was coated with a hydrophobic self-assembly monomer OTS. And then, approximately 20 μL cm^{-2} silicone oil was dip-coated on the functionalized stainless steel textured surface to create LIS. The liquid could completely wet the textured surface via capillary force from the structures. Before anti-adhesion evaluation, the liquid-infused substrate was vertically placed for 5 h to drain off the excessive liquid.

2.4. Anti-adhesion evaluation of the prepared LIS

To evaluate the anti-adhesion effects of the prepared LIS, an adhesion force measurement platform was built, as shown in Fig. 2a. Lean meat of the pig was cut into a circular shape with diameter of approximately 3 cm (thickness approximately 1 cm) and fixed on a mobile cylindrical base which was controlled by a micromanipulator (MX7600R, SISKIYOU, American). The test sample was fixed on a temperature-control heating stage equipped with a force transducer (9256c1, KISTLER, Switzerland). For adhesion force measurement, the soft tissue was loaded on the test surface and then unloaded at a speed of 500 μm s^{-1}. The loading pressure and adhesion force (unloading pressure) were recorded by a computer, connected with the force transducer. Fig. 2b shows a typical force measurement curve, and loading pressure and adhesion force correspond the peak value of force measurements in the loading process and the unloading process, respectively. Each adhesion force data came from five individual measurements.

2.5. Morphology, wettability, and solid-liquid interface characterization

Surface morphologies of the textured surfaces were characterized using a scanning electron microscope (SEM, JSM-6010, JEOL, Japan). An optical contact angle measuring system (SL200B, Solon, China) was applied to measure the contact angle (CA) and the sliding angle (SA) with water droplets (4 μL). The high-temperature resistance of silicone oil with different kinematic viscosities was evaluated by adding 2 g silicone oil on the hotplate at the temperature of 300 °C, and the volatilization mass ratio was obtained by measuring the mass change of silicone oil after 2 min. A scanning white-light interferometer (SWLI) was employed to scan the three-dimensional surface morphologies of the textured surfaces.

3. Results and discussion

Soft tissue adhesion on the electrosurgical instruments mainly arise on the instrument tip, such as the tips of the electrode and the forceps, which are generally made of stainless steel. So, we use the stainless steel as the substrate to investigate the anti-adhesion effects of the LIS. For preparing LIS, surface structures