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Antifriction effect of 316L stainless steel textured surface with superhydrophilic properties in brain tissue insertion

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Abstract

To reduce the tissue damage caused by the cannula electrodes during the operation of deep brain stimulation, laser matching micro texture on the surface of the electrodes was proposed to reduce the friction force. Different grooves and pit arrays were fabricated on the 316L stainless steel surface using an ultra-violet nanosecond laser. The wettability of textured surfaces with different morphologies was measured by distilled water and artificial cerebrospinal fluid. Insertion experiments were carried out on porcine brains using textured steel needles. The results showed that textured steel needles have an obvious antifriction effect under the condition of the lubricant. The elliptical pit texture has the best effect of reducing friction, and the friction force can be reduced by 37.6% on average.

1. Introduction

Deep brain stimulation (DBS) is an effective surgery for Parkinson’s disease. In DBS surgery, a cannula electrode is inserted into the brain to serve as a guide. During the insertion, the electrode may cause mechanical damage of the blood vessel or brain tissue, and generate corresponding acute or chronic pathological reactions such as cerebral hemorrhage and brain edema [1, 2]. The friction between the brain tissue and the cannula electrode is one of the important causes of tissue damage. Therefore, the reduction of friction can effectively reduce the insertion damage to the brain tissue.

To date, some surface textures with tiny bumps or ripples were found to affect the tribological properties in nature, such as the legs of the water strider and the skin of the snake. This has aroused the interest of many scholars. Their research shows that texturing treatment of the smooth surfaces with a certain morphology has a significant antifriction effect. The micro-texture can decrease the direct contact area between friction pairs, and also form micro-hydrodynamic lubrication bearings between friction pairs, thus forming diaphragms, further reducing friction [3, 4]. These findings are beginning to make their way into medicine. Inspired by mosquito mouthparts, K Oka et al. developed a kind of sawtooth hollow microneedle made of silica and carried out experimental research on the insertion force [5]. Cho et al. studied the bristles of porcupines, a needle-like structure with barbs, and manufactured a needle by imitating this structure. The results showed that the distributed barb can increase the stress concentration and decrease the insertion force [6]. Therefore, if the appropriate surface texture is machined on the DBS cannula electrode, the friction between the electrode and the tissue will be reduced, thus reducing the risk of surgery.

Due to the excellent properties such as high-temperature resistance, corrosion resistance, oxidation resistance, and excellent gloss [7–9] the DBS electrode is usually manufactured with 316L stainless steel [10, 11]. As many processing technologies can be applied to 316L, such as photolithography, surface deformation, electrochemical machining, laser machining, etc. [12–16]. Among them, laser machining has the advantages of simple processing, rapid processing favorable environmental cleanliness, good controllability, and other competitive advantages [17], so it has become the most promising surface texture processing technology. Laser deformation based on the ultrashort pulse, i.e. picosecond or femtosecond laser pulse, has been proved to be an
Table 1. Elemental composition of 316L SS used in the experiment.

| Element | C   | Si  | Mn  | P   | S   | Ni  | Cr  | Mo  | N   | Co  | Fe  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| wt%     | 0.02| 0.57| 1.56| 0.03| 0.03| 10.10| 16.76| 2.01| 0.06| 0.08| 68.78|

effective method to modify the surface morphology of materials in micro/nanoscale in a brief time [18]. At present, researchers usually use infrared nanosecond laser to process special surfaces, while ultraviolet (UV) laser is rarely used to change the surface morphology. UV laser has the advantages of high machining accuracy, low cost, no special requirements for equipment, etc., the most important thing is the negligible thermal effect in the process of laser deformation [19]. Therefore, it is of great value to investigate the texture treatment of material surfaces by a UV nanosecond laser.

Among the numerous events that occur after the material is inserted into the human body, the first and most important is the wetting of the physiological liquid on the implant, because the wettability affects the adhesion of proteins and cells on the implant surface [20]. The in vitro researches also revealed that the tribological properties were strongly affected by the surface wettability of the material in an aqueous environment [21]. Therefore, people have actively researched and manufactured the surface with extremely low wettability, which is called superhydrophobic, or the surface with extremely high wettability also called superhydrophilic [22, 23]. The measure of the surface wettability is given by the Contact Angle (CA), defined as the angle between the solid-liquid interface and the liquid-vapor interface [24]. Some scholars have changed the surface morphology and wettability of alloy materials through laser processing and coatings [25–27], and the results showed that surface wettability is closely related to surface morphology and chemical composition [8, 28, 29].

In this paper, we fabricated microtextures of different shapes on the surface of 316L stainless steel using a UV laser. The CA of the textured surface was measured with different droplets, and based on this, appropriate parameters were selected for processing on steel needles. Using the porcine brain as material, the antifriction effect of textured steel needles was investigated through an insertion experiment, which verified the feasibility of applying this work to DBS surgery.

2. Experimental

2.1. Sample preparation

The wettability measurement experiment was carried out on the surface of the square block sample. The chemical composition of 316L SS used in the experiment is shown in table 1. The experiments were performed on 5 mm thick specimens of 316L SS with an area of 2.5 × 2.5 cm². The samples were ground with 400#, 600#, 1200#, 2500# sandpaper in turn on a disc type polishing machine, followed by metallographic polishing with W1 diamond abrasive paste. The processed steel sheet was placed in an ultrasonic cleaner and washed with absolute ethanol for more than 10 min, and then dried by a vacuum dryer. The surface roughness of the treated sample reached 0.1 microns or less.

The outer wall of the cannula electrode used in DBS operation is a SS hollow cylinder with a diameter of 1.5 mm. To facilitate the processing, the solid SS needle was used instead. The 316L SS needle of Φ 1.5 mm × 80 mm was cut by a cutting machine, fixed by a rotating holder, ground, and polished with fine sandpaper, flannelette, and diamond abrasive paste to the surface roughness ≤0.5 μm.

2.2. Laser processing

Figure 1 is the schematic diagram of the laser processing system (JPT, China). The sample was fixed on the horizontal table, and a two-mirror current measurement scanner system moved the beam to the sample. The distance between the sample and the lens was constant so that a spot with a fixed diameter of 20 μm can be obtained. The shape that needs to be processed was drawn by the software on the computer. The laser beam radiated the material surface along the processing path according to the drawing shape under the control of the numerical control system.

The laser scanning path is shown in figure 2. The microtextures processed include micro-grooves and micro-pits. In the process of micro-grooves, the scanning speed was used as a control variable to change the morphology of grooves. The shapes of pits processed include circles, squares, ellipses, and triangles of different structure sizes (D) and separation distance (A). The structure size corresponds to the diameter of the circle, the sides of the square and the triangle, and the axis of the ellipse respectively. The parameters of laser power, repetition rate, and pulse width were optimized by orthogonal experiment before processing and remained unchanged during the following machining. The specific laser processing parameters are shown in table 2 and table 3.
Table 2. Parameters used in machining micro-grooves.

| Machining parameter       | Value     |
|---------------------------|-----------|
| Repeat frequency (kHz)    | 40        |
| Pulse width (ns)          | 10        |
| Scanning speed (mm s⁻¹)   | 50/300/500|
| Average output power (W)  | 3         |
| Separation distance (μm)  | 100       |

Table 3. Parameters used in machining micro-pits.

| Machining parameter       | Value        |
|---------------------------|--------------|
| Repeat frequency (kHz)    | 40           |
| Pulse width (ns)          | 10           |
| Scanning speed (mm s⁻¹)   | 300          |
| Average output power (W)  | 3            |
| Structure size (μm)       | 50/100/200/300|
| Separation distance (μm)  | 50/100/200/300|
After observing the subsequent experimental results, the laser parameters for processing the SS needle were selected from the above parameters. A hollow rotating clamp with controllable rotation speed and angle was installed on the worktable of the laser processing system to meet the requirements of SS needle clamping and rotation during laser machining. The single scanning length was set as 40 mm, and the distance between the starting point of scanning and the end of the cylinder was about 0.5 mm, to avoid the cutting effect of surface texture on brain tissue. After processing the needles were polishing with sandpaper.

2.3. Sample characterization

The processed samples were washed with anhydrous ethanol for 10 min and dried naturally in the air. The overall morphology of the texture was observed with a laser scanning confocal microscope (LSM 800, German) and the depth and width of the pit were also measured. The equipment for measuring CA was the optical contact angle measuring instrument (SDC-100, China). Under the condition of 25 °C room temperature and 50% air humidity, the CA was measured by sessile drop technique with a 3 µl droplet. To simulate the operating environment of DBS, distilled water and artificial cerebrospinal fluid (ACSF) were used respectively [30]. The value of CA changes gradually with time so the measurement result was taken as the stable value after the 20 s to reduce the experimental error. To prevent the experimental results from being accidental, the measurement was repeated on different samples three times, and the results were averaged.

2.4. 316L SS needle insertion test

A brain tissue insertion experiment was carried out to verify the antifriction effect of surface texture. The porcine brain is similar to the human brain in structure and mechanical properties and is easy to obtain [31, 32]. Therefore, we selected fresh isolated porcine brains for the experiment. Porcine brains were selected from healthy live porcine slaughtered in standard procedures for about six months and immediately soaked in frozen ACSF to maintain brain activity. The purchase and use of porcine brains have been approved by the Animal Care and Use Committee of Qilu Hospital, Shandong University. And it has been conducted following the management and use standards of the National Health Guidance Center of China. The insertion experiment was carried out within six hours after the brain was isolated at room temperature. The arachnoid and pia mater in the insertion area should be gently peeled off before the insertion test.

The experimental device consists of a test platform, force sensor, driving system, and data analysis system, as shown in figure 3. A servo controller (PI, German) was installed on the z-axis of the three-axis engraving machine to control the precise vertical displacement. The force sensor was ATI industrial automation F/T sensor Nano17 with a resolution of 3mN. The raw or laser processed needles were installed on the force sensor through the drill chuck and then were moved to a position about 1 mm above the area to be inserted by the driving system. Afterward, the z-axis was moved down and the position of the steel needle was determined as the initial position of the experiment when the brain tissue was under 3mN pressure. At that time, the sensor was reset and started to collect the insertion force signal. According to the experience of surgeons in local medical institutions, the insertion speed, and needle withdrawal speed were set as 5 mm s⁻¹. The insertion and
withdrawal displacement was set as 50 mm and 60 mm, respectively, to ensure the complete withdrawal of the insertion needle from the brain tissue. The insertion experiment for each needle was repeated 10 times on different samples with or without ACSF lubricant and the needle was washed with distilled water and dried with test paper before reuse. This means 5 porcine brains were inserted with or without ACSF respectively. So a total of 10 porcine brains were inserted with six needles. The average value of insertion force was taken during the subsequent analysis.

3. Results and discussion

3.1. Morphological observations and topographic characterization

Figure 4 shows the SEM images of groove texture processed at different scanning speeds. It can be seen that when \( v = 50 \text{ mm s}^{-1} \), as shown in figure 4(a), the ablation effect is obvious, forming a thicker recast layer. As the slag height increases, the overlap of light spots cannot be observed, and the size of the splashing melt on both sides of the groove is larger. As velocity increases from 50 mm s\(^{-1}\) to 150 mm s\(^{-1}\), as shown in figure 4(b), the contours of light spots overlap together, still forming a dense groove bottom, and the covering at the bottom of the groove is relatively reduced. When velocity continues to increase to 300 mm s\(^{-1}\), as shown in figure 4(c), an obvious spot contour begins to appear at the bottom of the groove, and the melt recasting phenomenon of the material is significantly weakened.

Figure 5 shows the 20,000-fold SEM images of the bottom of the groove texture at different scanning speeds. When \( v = 50 \text{ mm s}^{-1} \), as shown in figure 5(a), the bottom of the groove was covered by layers of micron-sized aquatic herbaceous tissues, which were covered by fine nanocrystals. When \( v = 150 \text{ mm s}^{-1} \), as shown in figure 5(b), the aquatic plant-like tissue gradually disappeared and micron particles began to appear, and the size of nano-processes covered by the micron particles increased. When velocity further increases to 300 mm s\(^{-1}\), as shown in figure 5(c), the aquatic herbaceous tissue completely disappears, the melt distribution is relatively dispersed, and the size of nano-particles further increases.

With the increase of scanning speed, the groove width fluctuates repeatedly in a small range, the maximum value is 23 \( \mu \text{m} \), the minimum value is 21.62 \( \mu \text{m} \), and there is no obvious change rule. The depth of grooves decreased sharply from 7 \( \mu \text{m} \) to 1.23 \( \mu \text{m} \) with the increase of scanning speed, which varied greatly.
Figure 6 is a laser confocal microscopic image of surface texture with a structure size of 200 μm and a separation distance of 200 μm. It can be seen from the figure that the processed texture shape and size are consistent with the preset pattern. Due to the high energy density, the surface material vaporization produced more slag, resulting in the gradual production of prominent melt at the edge of the texture. Under certain conditions, the phase explosion will dominate the material remelting process during laser machining. This regime can result in a severe plasma shielding effect in the ablation region. The plasma plume continues to absorb the laser energy in various ways, shielding the area from laser radiation. Heat cannot be diffused in time in the irradiated area, which further produces a thermal hatching effect, resulting in the uneven sidewall and the formation of slag blocks at the bottom of the pit. Figure 6(e) shows the cross-section profile of the processed pit. The depth from the top of the slag to the bottom of the pit center is 1 μm, while the distance from the slag to the bottom of the pit near the contour is 2 μm. Due to the setting of the processing software, the contour line of the pattern will be processed again after processing the area covered by the texture, so the processing depth of the area near the contour line is relatively large.

3.2. Surface wettability variation
Figure 7 shows the CA of distilled water and ACSF on a smooth surface without texture. 316L SS is a weakly hydrophilic material, and the contact angle of both droplets is slightly less than 90°. Since ACSF has a higher viscosity than distilled water, the CA of ACSF is slightly larger than that of distilled water.

The contact angles measured by distilled water and ACSF were 0° on the grooved textured surfaces prepared at different scanning speeds. Although the surface is super hydrophilic, the droplet spreading state is very
different. When the scanning speed is low \((v = 50 \text{ mm s}^{-1})\), the droplets on the surface completely penetrate the groove at a very fast speed, and the traces of the droplets on the surface are linear, while the droplets on the rest of the ultra-hydrophilic surface are spread out into liquid film. For ease of distinction, the surface wettability of the droplet rapidly and completely infiltrating into the groove is called extreme hydrophilic.

Figures 8 and 9 show the CA of distilled water and ACSF on surfaces with different texture sizes and spacing. It can be seen from the figure that when the texture size is unchanged, the CA of all patterns increases with the increase of separation distance. And when the separation distance is constant, the CA of all patterns decreases with the increase of texture size. When the separation distance is less than or equal to 100 \(\mu\text{m}\), the CA of liquid on all kinds of micro-texture surfaces is 0°, except the elliptic array and triangular array with the size of 50 \(\mu\text{m}\). The surface of circular pits and square pits is more hydrophilic than that of elliptic and triangular arrays. Distilled water and ACSF showed the same variation trend on various surfaces.

T young put forward the famous Young’s equation based on the study of the capillary phenomenon and surface tension [34]:

![Distilled water and ACSF on surfaces](image)

**Figure 7.** Image of the CA of distilled water and ACSF on a smooth surface.

![CA of distilled water on different textured surfaces](image)

**Figure 8.** CA of distilled water on different textured surfaces. (a) Structure size = 50 \(\mu\text{m}\). (b) Structure size = 100 \(\mu\text{m}\) (c) Structure size = 200 \(\mu\text{m}\) (d) Structure size = 300 \(\mu\text{m}\).
In the equation, $\gamma_{sv}$, $\gamma_{sl}$, and $\gamma_{lv}$ are the interfacial tension of the solid-gas interface, the solid-liquid interface, and the liquid-gas interface respectively. The CA at this point is called the intrinsic CA of the material. The suitable object of the Young equation is the ideal uniform, smooth and rigid surface. However, in practical engineering applications, the material surface is not uniform and smooth, but anisotropic and rough, so the solid-liquid CA on the solid surface is not the intrinsic CA calculated by Young's equation. Wenzel attributed the difference between the apparent solid-liquid contact Angle of the actual surface and the intrinsic solid-liquid CA of the ideal surface to the existence of the roughness of the actual surface $[35]$: it was believed that the roughness of the actual surface caused the increase of the real solid-liquid contact area and the increase of the interface energy between the solid and liquid and the solid and gas, resulting in the change of the solid-liquid CA. At equilibrium, the relationship between the apparent CA and the intrinsic CA is:

$$\cos \theta_i = \frac{\gamma_{sv} - \gamma_{ld}}{\gamma_{lv}}$$  \hspace{1cm} (1)

where $\gamma_{sv}$ is the interfacial tension of the solid-gas interface, $\gamma_{ld}$ is the interfacial tension of the liquid-gas interface, and $\gamma_{lv}$ is the interfacial tension of the solid-liquid interface.

In the equation, $\gamma_{sv}$, $\gamma_{ld}$, and $\gamma_{lv}$ are the interfacial tension of the solid-gas interface, the solid-liquid interface, and the liquid-gas interface respectively. The CA at this point is called the intrinsic CA of the material. The suitable object of the Young equation is the ideal uniform, smooth and rigid surface. However, in practical engineering applications, the material surface is not uniform and smooth, but anisotropic and rough, so the solid-liquid CA on the solid surface is not the intrinsic CA calculated by Young's equation. Wenzel attributed the difference between the apparent solid-liquid contact Angle of the actual surface and the intrinsic solid-liquid CA of the ideal surface to the existence of the roughness of the actual surface $[35]$: it was believed that the roughness of the actual surface caused the increase of the real solid-liquid contact area and the increase of the interface energy between the solid and liquid and the solid and gas, resulting in the change of the solid-liquid CA. At equilibrium, the relationship between the apparent CA and the intrinsic CA is:

$$\cos \theta_a = r \cos \theta_i$$  \hspace{1cm} (2)

Where $r$ is Wenzel roughness rate, the ratio between the real contact area of solid and liquid, and the apparent contact area of solid and liquid. According to the Wenzel model, surface textural treatment makes the hydrophilic surface more hydrophilic and the hydrophobic surface more hydrophobic. 316L SS is a weak hydrophilic material, which will become more and more hydrophilic with the increase of surface roughness. The $r$-value of the grooves processed at different scanning speeds increases, so the surfaces are all superhydrophilic. When the scanning speed is low, the depth of the groove increases significantly, so the process of droplets penetrating the groove is faster and more obvious. For pit textured surfaces, the increase of texture area and the decrease of texture spacing increase the distribution rate of surface texture, make the surface rougher, and thus enhance the surface hydrophilicity. According to our processing rules, the area of circular and square pits is significantly larger than that of elliptic and triangular pits, resulting in greater roughness of the former than of the latter, thus making the former more hydrophilic.

### 3.3. Antifriction effect of textured steel needle

According to the experimental results of 3.2, we used speeds of 300 mm s$^{-1}$ to produce superhydrophilic grooved textured surfaces. For pit textured surfaces, the surfaces of all patterns can achieve super hydrophilicity when the appropriate texture spacing and texture size are selected for processing. Considering machining
accuracy and efficiency, we set the separation distance and the structure size to 100 microns. The processed steel needle is shown in figure 10. It can be seen that the texture of the four patterns processed on the surface of the needle is relatively regular. Figure 11 shows the insertion of the porcine brain with a steel needle. To study the effect of hydrophilicity on friction reduction, insertion experiments were carried out in the condition of ACSF lubrication. The porcine brain was completely immersed in the ACSF to accurately simulate the scene of human brain insertion.

Figure 12 shows the insertion force curve measured by the sensor. The abscissa is the data collection point, and the ordinate is the longitudinal force of the needle. After the contact of the steel needle with the brain tissue, the cortical surface of the brain sinks, and the stress of the needle increases. When a steel needle inserts the cortex, the insertion force bounces back. The same change occurs when the needle reaches and pierces the base of the porcine brain. After piercing the bottom of the porcine brain, the insertion force will stabilize at a certain value, that is, the part circled by the red line in figure 12. This force represents the friction force applied to the needle as it moves through the porcine brain. In general, the friction force will increase with the increase of the thickness of the porcine brain, so the friction force cannot be directly used to represent the antifriction effect. To make the result more scientific and reasonable, the ratio of friction force to penetration depth, i.e. $F_l$ the friction force per unit length of the steel needle, was used as the index to measure the anti-friction effect.

Figure 10. Textured steel needle with different patterns (a) Groove texture (b) Circular texture (c) Square texture (d) Elliptic texture (e) Triangular texture.
The penetration depth $h$ is calculated by equation (3).

$$h = \frac{(n_i - n_0)}{f_z}v$$

(3)

The formula of $F_l$ is:

$$F_l = \frac{Ff_z}{(n_i - n_0)v}$$

(4)

Where $F$ is the force in the red circle in the figure, $f_z$ is the data sampling frequency of the sensor, and $v$ is the insertion speed of the steel needle. $n_0$ and $n_i$ are respectively data points at the beginning and end of the pure friction stage.

The insertion results are shown in figure 13. Under the condition of ACSF lubrication, the textured surfaces of all types of steel needles significantly reduced friction. Among them, the most obvious anti-friction effect is still the elliptical array of steel needles, which reaches 37.6%. This indicates that the textured surface with super hydrophilicity properties has a good anti-friction effect. Groove textured needles also showed obvious friction reduction.

When processing micro-texture, we selected appropriate processing parameters, and the slag height and texture depth formed was relatively small, which would not produce a pulling and hooking effect on brain tissue. Due to the existence of surface texture, the contact area between textured steel needles and brain tissue during insertion is smaller than that of smooth needles, so the friction force will be reduced correspondingly. However, this kind of anti-friction effect is relatively limited. When the insertion is performed under the condition of ACSF lubrication, the ACSF will enter the pit to form an effective liquid-lubricated bearing and a diaphragm between the friction pairs, thus significantly reducing the friction between the insertion needle and the brain tissue [36]. We have made the following conjecture as to the influence of the pattern of surface texture on the anti-friction effect: Compared with other shapes of micro-texture, elliptic micro-texture has obvious transverse and longitudinal ratio, which is more conducive to the formation of liquid-lubricated bearings. Therefore, machining an elliptic array on the surface of the steel needle will get the best anti-friction effect. Compared with other surfaces, the extremely hydrophilic surface has a larger slag, so the friction reduction effect cannot be achieved. It is worth noting that the error range of the experimental results is large. This is because the tissue structure inside the porcine brain is relatively complex and anisotropic, and the steel needle will contact different tissues when insertion experiments are carried out at different positions, so the results obtained are biased. In addition, the mechanical properties of different porcine brains themselves have certain differences. In the subsequent studies, isotropic materials will be used to simulate porcine brain tissue to further verify the antifriction effect of textured steel needles. This study is subject to several important limitations that should

![Figure 11](image-url)
influence the interpretation of these results. The brain used in this study is harvested from porcine (6-month-old, weight 70–80 kg). Due to the similar anatomic and mechanical properties, porcine brains can act as substitutes for human brains. While the ages and species that some researchers reported would affect the mechanical properties of brain tissue were neglected in this paper [37]. Future work will build an insertion mathematical model with different species and ages.

Figure 12. (a) Diagram of insertion force in the process of porcine brain insertion (b) insertion friction force of different needle with ACSF lubricant.
4. Conclusions

In this work, the texture of different shapes was machined on 316LSS using an ultra-violet nanosecond laser machining platform. The super hydrophilicity surface was successfully prepared by selecting proper processing parameters. Using a textured steel needle, an insertion experiment was carried out on a self-made insertion experiment platform with the porcine brain as material. The results show that when using ACSF as a lubricant, the textured needles of various patterns significantly reduced the friction between the needle shaft and the tissue compared to smooth needles. Among them, the steel needle with an elliptic array on the surface has the best anti-friction effect, decreasing by 37.6% on average. In the follow-up study, we will further study the effect of steel knitting on tissue damage, to verify the possibility of applying this study to DBS surgery.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Figure 13. The force of friction per unit length of various steel needles with or without ACSF.
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