

Tribological properties of textured stator and PTFE-based material in travelling wave ultrasonic motors

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Abstract: This study fabricated textures on the stator surface of a traveling wave ultrasonic motor (USM) using laser and investigated the tribological behavior of a polytetrafluoroethylene (PTFE) composite friction material and stator. Initially, the effect of textures with different densities was tested. As the results suggested, the generation of large transfer films of PTFE composite was prevented by laser surface texturing, and adhesive wear reduced notably despite the insignificant decrease in load capacity and efficiency. Next, the 100-h test was performed to further study the effects of texture. Worn surface and wear debris were observed to discuss wear mechanisms. After 100 h, the form of wear debris changed into particles. The wear mechanisms of friction material sliding against the textured stator were small size fatigue and slight abrasive wear. The wear height of friction material decreased from 3.8 μm to 1.1 μm . This research provides a method to reduce the wear of friction materials used in travelling wave USMs.

Keywords: laser surface texturing; ultrasonic motor; PTFE-based material; friction; wear mechanisms

1 Introduction

The ultrasonic motor (USM) is a type of piezoelectric actuator that drives a rotor by the frictional force at the interface between the rotor and stator [1–3]. When compared with an electromagnetic motor, the USM has the advantages of compact structure, low speed, high torque, quick response, and high-power density. It is widely applied in aerospace, micro-electromechanical systems, and optical precision engineering [4–8]. However, owing to the driving principle, the wear of stator and rotor is inevitable, which strongly impacts the lives and performances of USMs [9, 10]. These tribological issues in USMs have attracted substantial attention, and many interesting results have been achieved.

Polytetrafluoroethylene (PTFE), a plastic material, exhibits excellent anti-wear property and low frictional

coefficients. Even at cryogenic temperatures, PTFE possesses good wear resistance [11]. Because low values of friction coefficient and wear rate are required in travelling wave USMs, PTFE filled with additives is usually used as friction material for travelling wave USMs. Fan et al. [12] investigated the wear properties of a PTFE material used in USMs with different contents of filled potassium titanate whiskers (PTWs), and a preferable content was found. Ding et al. [13] proposed polyvinylidene fluoride composites as friction material for USMs, and the anti-irradiation property of the material was studied. Wang et al. [14] investigated the impact of fillers and counter-face topography on the wear behavior of PTFE polymers for USMs. Song et al. [15] investigated the tribological performance of a filled PTFE-based friction material for a USM under different temperature and vacuum degrees, and found that the adhesive wear was prone to take

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place under high vacuum degrees. Li et al. [16, 17] investigated the wear properties of a PTFE composite used in USMs and found that the wear mechanism of rotor friction material is very different from that of stator friction material owing to the differences in their contact mechanisms.

Although, the studies mentioned above have presented an in-sight of the tribological problems in the actuators, only a few practical ways have been proposed to improve the tribological properties of friction materials applied in USMs.

Recently, laser surface texturing has emerged as a potential new method to improve the tribological properties of mechanical components. Laser surface texturing is used to improve the tribological properties of coatings, ceramics, and metallic materials [18–21]. The effects of laser surface texturing on the thickness of lubricant film were also investigated [22–24]. Gropper et al. [25] reviewed the key findings in texture design and modelling techniques, which provides an important contribution to the research of texture. Laser surface texturing was also used to research the relationship between the tactile friction and perceptual attributes [26, 27].

The beneficial and detrimental effects of surface texture depend certainly on the types of tribo-pairs. The same surface texture may exhibit an inverse effect under different conditions. Vlădescu et al. [28, 29] researched the flow behavior of a lubricant in a reciprocating contact, simulating a piston ring–cylinder liner pair. They concluded that an appropriate choice of surface texture pattern is capable of reducing not only piston–cylinder liner friction but also automotive oil consumption, and the pocket spacing on piston liners should be varied as a function of the reciprocating sliding speed. Furthermore, it was found that the pockets tend to increase fluid entrainment and reduce any asperity contact but pockets at reversal tend to increase friction dramatically [30]. Braun et al. [31] investigated the tribological behavior of steel sliding pairs with dimple diameters, ranging from 15 mm to 800 mm, in a mixed lubrication regime in a pin-on-disk experiment. The results showed that the dimple diameters leading to the highest friction reduction significantly depend on the oil temperature.

The tribo-pairs of rotor and stator in USMs are special

by the virtue of ultrasonic vibrations. The method to design the texture on a stator surface to obtain better tribological properties is still not clear, which is the purpose of this study. The dimple textures were fabricated on the stator surface of a travelling wave USM using laser. To study the effects of laser surface texturing on the tribological performances of USMs, the speed and efficiency characteristics were tested, and the worn surface and wear debris were observed. This research also introduces a wear reduction method for travelling wave USMs.

2 Experimental details

2.1 Tribo-pairs and surface texturing

A travelling wave USM (USM60-2, Xi'an Chuanglian Ultrasound Technology Co., Ltd) was applied in this study. The tribo-pairs of stator and rotor are shown in Fig. 1. The stator and friction material were made of bronze and PTFE-based composite, respectively. The Shore hardness of the PTFE-based friction material was nearly 75, as tested using a Shore hardness tester.

Dimples on the stator surface were fabricated using Nd: YAG laser. The electric current was set as 220 A, pulse width as 0.2 ms, and frequency as 2 Hz. The textures are shown in Fig. 2. Two types of textures were fabricated on the stator: a one-line dimple texture (texture-1L) (Fig. 2(a)) and three-line dimple texture (texture-3L) (Fig. 2(b)). The texture area densities of the one-line dimple and three-line dimple textures were approximately 7.95% and 23.85%, respectively.

After investigating the characteristics of the stator employing texture-1L, the stator was cleaned using an ultrasonic cleaner, and then texture-3L was fabricated. The topography of a dimple is shown in Fig. 2(c) and its profile is shown in Fig. 2(d). The height and width of the dimple were nearly 180 μm and 340 μm , respectively.

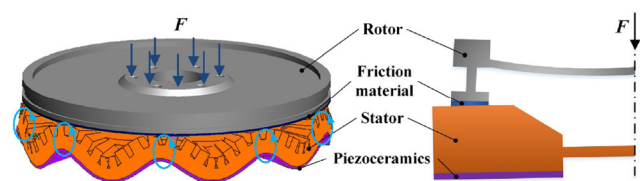


Fig. 1 Tribo-pairs of stator and rotor in a USM.

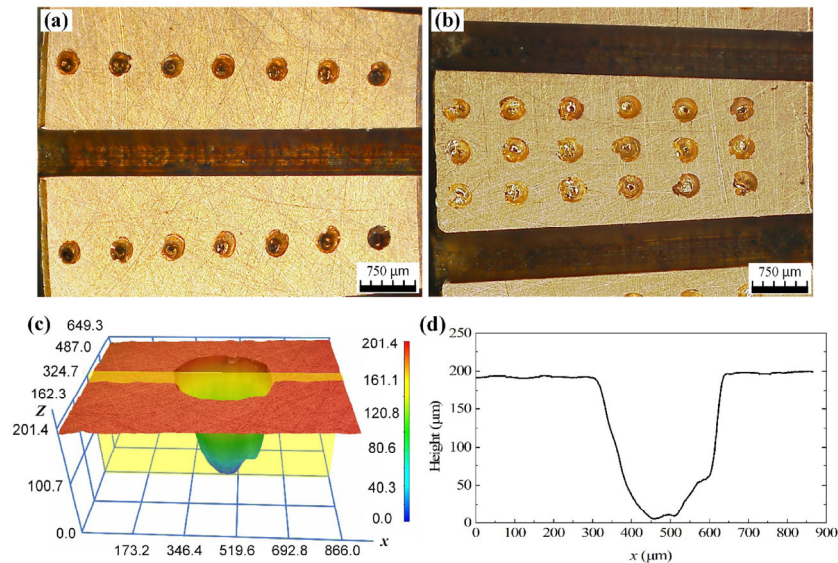


Fig. 2 Surface textures on stator surface: (a) texture-1L and (b) texture-3L; (c) 3D topography of dimple; (d) profile of dimple.

2.2 Experimental setup

An experimental setup, capable of controlling the preload between the stator and rotor accurately, was used to test the performance of the USM. The experimental setup is shown in Fig. 3. The principle and structure of the experimental setup have been introduced in our previous research [16]. The experimental setup primarily consisted of dovetail rails, a micrometer head, pressure sensor, speed-torque sensor, and magnetic brake. The speed and torque of the USM can be measured under different preloads using this experimental setup.

3 Results

3.1 Performance of USM

The preload applied on the stator and rotor was set as 250 N, and the frequency of drive voltage was set as 39.6 kHz. Next, the speed-torque and efficiency-torque characteristics were tested, as shown in Fig. 4. The speed-torque characteristics of the textured stator decreased as compared to the non-textured stator. An apparent drop in speed (17.09 rpm) occurred when a torque of 0.35 N·m was applied on the stator with texture-3L, as shown in Fig. 4(a). The efficiency-torque characteristics of the motor also decreased with the increase in texture density. The maximum efficiencies

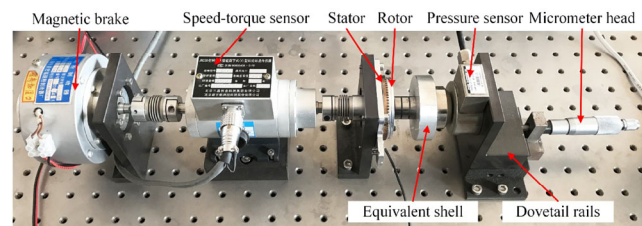


Fig. 3 Preload-controlled USM experimental setup.

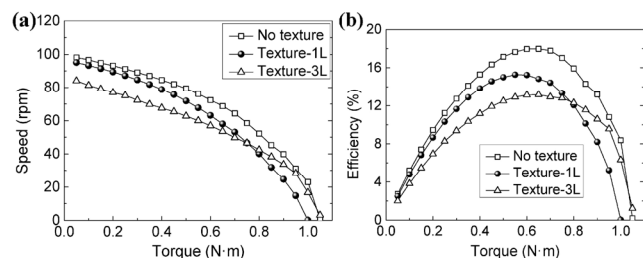


Fig. 4 Speed (a) and efficiency (b) of USM under different torques with textures on stator surface.

of the non-textured stator and stator with texture-3L differed by 4.81%. However, the stall torques of the stator with different textures were similar. When the torque was small, the efficiency of the stator with texture-3L was less than that of the stator with texture-1L, and when the torque was increased, the efficiency of the stator with texture-3L became higher than that of the stator with texture-1L.

3.2 Worn surfaces

The worn surfaces of the non-textured, texture-1L,

and texture-3L stators are shown in Fig. 5. Large pieces of transfer film were found on the surface of the non-textured stator (Figs. 5(a) and 5(d)). A few debris was found on the external edge of wear scar on the stator with texture-1L (Fig. 5(b)), and a very few particles of debris fell into the dimples (Fig. 5(e)). Fewer debris was found on the external edge of wear scar on the stator with texture-3L (Fig. 5(c)), and some debris fell into the dimples (Fig. 5(f)). The results suggested that the texture fabricated on the stator surface could greatly decrease the transfer of friction material, which, consequently, could increase the wear of friction material.

3.3 100-h test

To further study the effects of texture, the stator with no texture and the stator with texture-3L sliding against friction material were tested for 100 h. During the time period of 100 h, the wear debris and the surface topography of the stators were observed every 5 h from 0–40 h and every 20 h from 40–100 h. The preload applied on the stator and rotor was 250 N, the frequency of drive voltage was 39.6 kHz, and no torque was applied in the motor except when the speed-torque characteristics were tested.

3.3.1 Speed and torque

During the time period of 100 h, the speed of the motor was measured under the sampling frequency of 0.5 Hz.

The speed curves of the stators with no texture and texture-3L are shown in Fig. 6. The preload was set as 250 N. In the beginning, the speed of the stator with texture-3L was approximately 10 rpm less than that of the non-textured stator. The speed of the stator with texture-3L increased marginally with time, and the difference decreased to approximately 3 rpm after 100 h. Moreover, fluctuations in the speed of the textured stator were smaller than those of the non-textured stator, which suggested that the texture on the stator surface increased the stability of the USM.

The load-torque and efficiency-torque characteristics were tested after 5 h and 100 h, as shown in Fig. 7. After 5 h, the difference in the efficiency of the two speed curves decreased with the increase in torque, as shown in Fig. 7(a). After 100 h, the two speed curves appeared very close, as shown in Fig. 7(b). The difference in efficiencies decreased with time. After 5 h, the maximum efficiency of the non-textured stator was 22.9% with torque of 0.5 N·m, whereas the value of the textured stator decreased to 18.2% with torque of 0.65 N·m. The difference in maximum efficiencies was about 4.7% after 5 h, whereas the difference decreased to 3.7% after 100 h (Figs. 7(a) and 7(b)).

3.3.2 Evolution of surface topography

During the 100-h test, the surface topography of the stator was observed under a digital microscope (KH-8700, QUESTAR Co., Ltd.), as shown in Fig. 8.

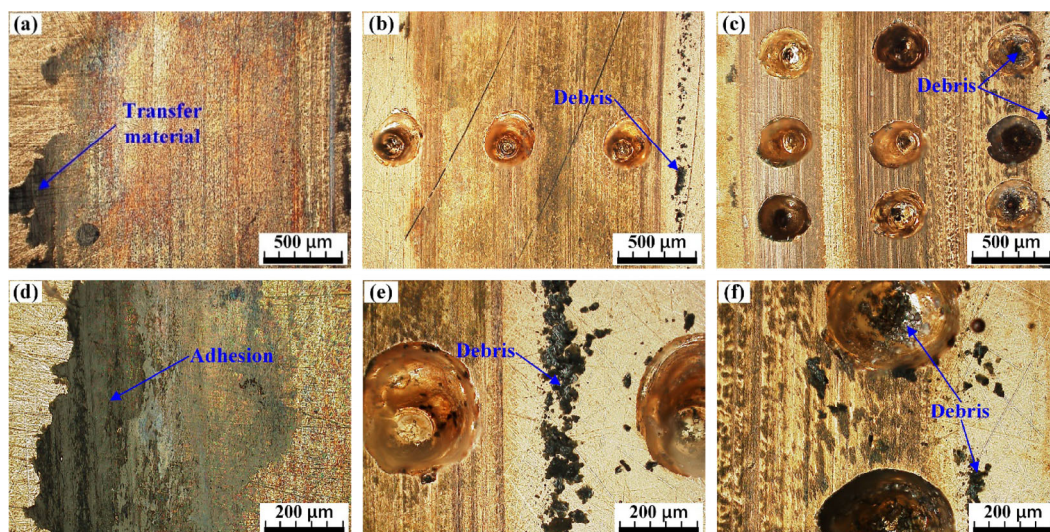


Fig. 5 Worn surfaces of stator with different textures under low magnification: (a) no texture, (b) texture-1L, and (c) texture-3L; and under high magnification: (d) no texture, (e) texture-1L, and (f) texture-3L.

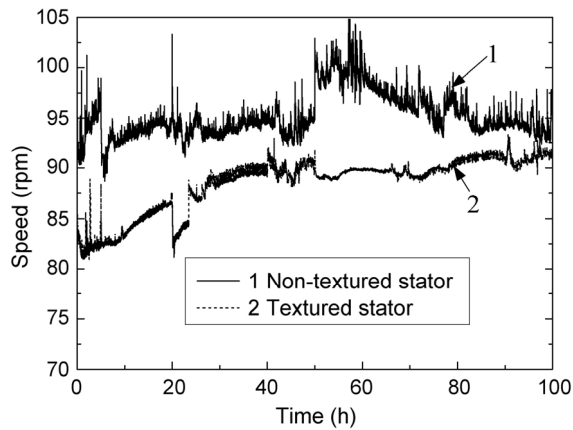


Fig. 6 Speed of USM in 100-h test.

After 5 h and 20 h, large pieces of transfer film were found on the surface of the non-textured stator (Figs. 8(a) and 8(b)). Even 100 h later, some transfer films were found, as shown in Fig. 8(c). A large transfer film could be not generated on the textured stator

surface. After 5 h, only a few particle-like debris existed outside the wear scar, as shown in Fig. 8(d). After 20 h, the debris became fewer (Fig. 8(e)), and a few fog-like debris were found in the dimples after 100 h (Fig. 8(f)). It was found that the transfer film of friction material decreased remarkably by the texture fabricated on the stator surface, as compared to the evolution of the surface topography.

After the 100-h test, the worn surface of friction material was observed using SEM, as shown in Fig. 9. Many cracks were observed on friction material sliding against the non-textured stator, as shown in Fig. 9(a). After 3,000 times magnification, cracks and debris were seen clearly around the cracks (Fig. 8 (b)). Cracks on friction material sliding against the textured stator decreased immensely, as shown in Fig. 9(c). Although some cracks were found on friction material, the surface was relatively flat, and no obvious debris existed

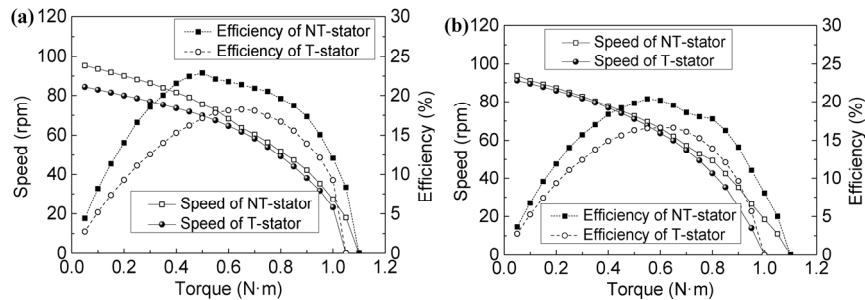


Fig. 7 Load and efficiency of USM under different torques after: (a) 5 h and (b) 100 h (NT-stator = non-textured stator, T-stator = textured stator).

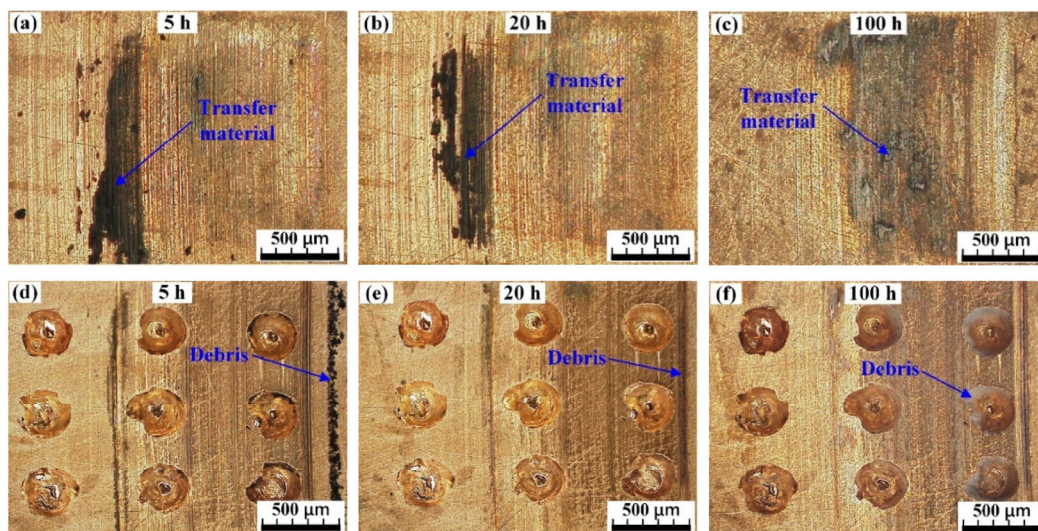


Fig. 8 Worn surface of non-textured stator surface after (a) 5 h, (b) 20 h, and (c) 100 h; worn surface of textured stator surface after (d) 5 h, (e) 20 h, and (f) 100 h.

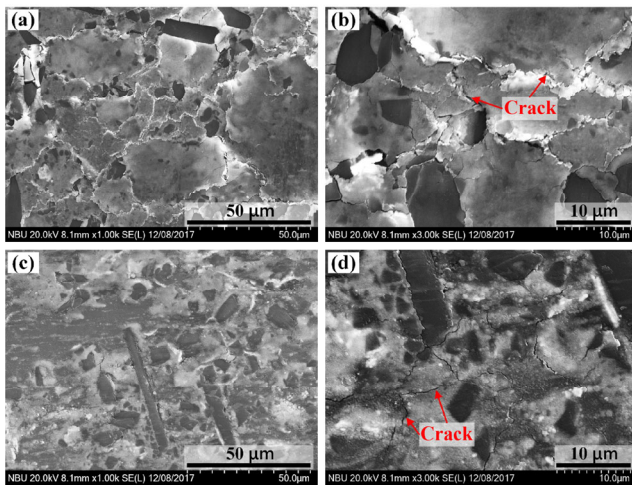


Fig. 9 Worn surface of friction material: sliding against non-textured stator magnified (a) 1,000 times and (b) 3,000 times, sliding against textured stator magnified (c) 1,000 times and (d) 3,000 times.

around the cracks (Fig. 9(d)). According to the results, the surface and subsurface of friction material were not seriously damaged when friction material slid against the textured stator. Accordingly, large pieces of adhesive material were avoided on the surface of the textured stator.

The thickness of the rotor was measured before and after the 100-h test using a digital micrometer with an accuracy of ± 0.002 mm. Eight equally spaced positions of the rotor were selected to measure the thickness, as shown in Fig. 10. Rotor-1 was slid against the non-textured stator, and rotor-2 was slid against the textured stator. The average wear heights of friction materials bonded on rotor-1 and rotor-2 were $3.8 \mu\text{m}$ and $1.1 \mu\text{m}$, respectively. The wear decreased significantly owing to the texture fabricated on the stator. The negative values of wear may be attributed to the plastic deformation.

3.3.3 Evolution of wear debris

The wear debris was collected and observed using SEM after being sprayed with Platinum, as shown in Fig. 11. The debris generated after 5 h from friction material sliding against the non-textured stator was a multilayer agglomerate sheet, as shown in Fig. 11(a). After 100 h of experiment, the size of debris decreased, and its form changed to particle-like (Fig. 11(b)). The size of debris generated from friction material sliding against the textured stator was smaller than that of friction material sliding against the non-textured

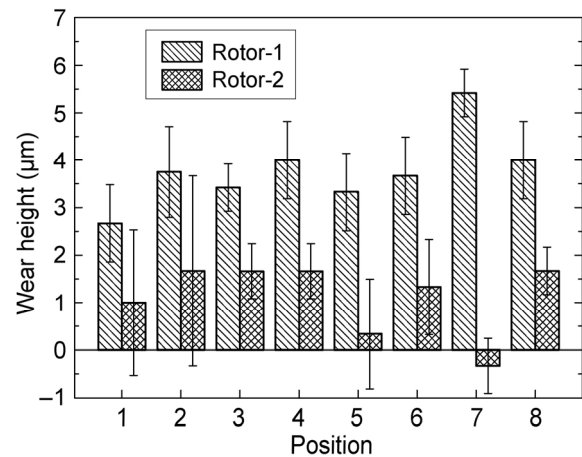


Fig. 10 Thickness of friction material at different positions.

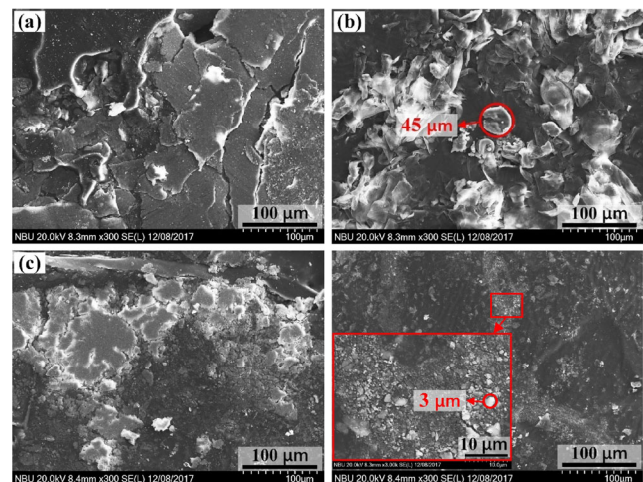


Fig. 11 Wear debris of friction material: sliding against non-textured stator after (a) 5 h and (b) 100 h, sliding against textured stator after (c) 5 h and (d) 100 h.

stator, as shown in Fig. 11(c). The size of debris collected from the stator surface (Fig. 8(f)) after 100 h was below several micrometers. Since the wear debris generated after 100 h from friction material sliding against the textured stator was very meager, a picture with more multiples ($\times 3,000$) was used to study the details, as shown in Fig. 11(d).

The debris of friction material shown in Fig. 11(b) was analyzed using the energy dispersive spectroscopy (EDS). The observed map spectrum is shown in Fig. 12. The contents of fluorine (F), carbon (C), and copper (Cu) elements are mentioned below the figures. Fluorine accounted for 61.1 at% and 62.5 wt%, and carbon accounted for 34.7 at% and 23.8 wt%, which suggested that most of the debris was generated from friction material. Copper, which came from stator only,

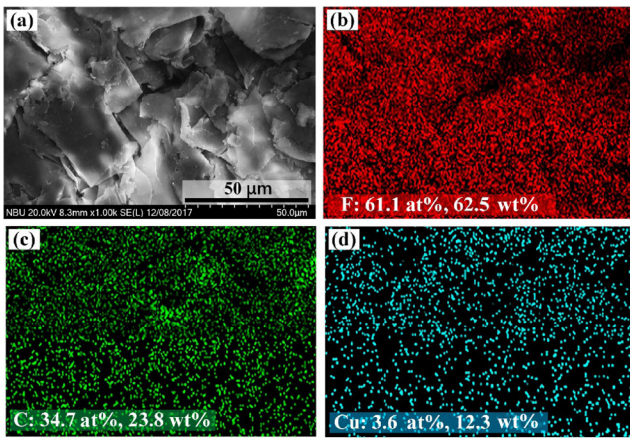


Fig. 12 EDS map spectrum of wear debris: (a) SEM photo of wear debris, (b) F element map spectrum, (c) C element map spectrum, and (d) Cu element map spectrum.

accounted for 3.6 at% and 12.3 wt%, which suggested that there was a slight wear of bronze stator.

4 Discussion

4.1 Effect of surface texture on performances of USM

Two types of surface textures were fabricated on the stator surface, and the speed-torque and efficiency-torque characteristics were tested and compared with the characteristics of non-textured stator. It can be seen from Fig. 4 that the performance of USM decreased by a small extent when the textures were fabricated on the stator surface. However, during the 100-h test, the non-load speed of the USM with the textured stator increased with time, and its speed was very close to that of the motor with the non-textured stator after 100 h (Fig. 6). After the test, the speed-torque characteristics of the textured stator and non-textured stator were also very close, except when the value of torque reached over 0.8 N·m (Fig. 7(c)). The difference in efficiency-torque characteristics decreased, however, a difference of 3.7% in maximum efficiencies still existed. These were primarily attributed to the friction reduction effect of surface texture. It is known that the USMs are driven by frictional force, and the reduction in frictional force decreases their speed and efficiency.

The friction coefficients of friction material sliding against the textured and non-textured stators were

measured without vibrations using the preload controlled USM test device (Fig. 3). The magnetic brake was replaced by a direct current (DC) motor. The normal load was set as 200 N and the speed was set as approximately 30 rpm in the test. The friction coefficients of friction material sliding against stators with no texture, texture-1, and texture-3L were 0.180, 0.179, and 0.175, respectively. This result confirmed that the textures fabricated on the stator surface reduced the friction.

4.2 Effect of surface texture on wear characteristics

The texture can significantly reduce the adhesive wear of friction material, as suggested by the results shown in Fig. 5. The changes in debris suggest the changes in wear mechanisms. The main wear mechanisms of PTFE-based material are adhesive wear and abrasive wear under no vibration friction condition [32, 33]. Because of the alternating contact of stator and rotor, the main wear mechanisms of PTFE-based friction material used in USMs are adhesive wear and fatigue wear [16]. In this study, the adhesive wear was prevented by the textures, and the main wear mechanism of friction material changed to small size fatigue and slight abrasive wear. The contact and wear mechanism of friction material is shown in Fig. 13. The cracks attributed to the fatigue occurred easily on the surface and subsurface of the material owing to ultrasonic vibrations as the internal bond force of the material caused a decrease in the crack growth. Small pieces of material were peeled off from the surface of friction material under the influence of the adhesive force.

Furthermore, the adhesive force can increase the growth of cracks. As a result, large pieces of transfer material were found on the surface of stator (Figs. 5(a) and 5(d), and Figs. 8(a), 8(b), and 8(c)), and the wear debris appeared as a multilayer agglomerate sheet (Figs. 11(a) and 11(b)). There were numerous cracks on friction material, and the material around the cracks was warped (Figs. 9(a) and 9(b)).

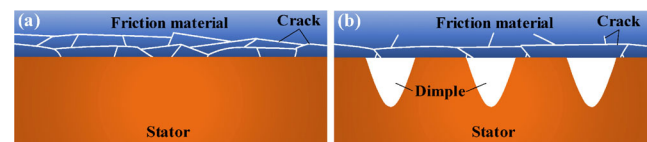


Fig. 13 Contact and wear mechanism of friction material sliding against (a) non-textured stator and (b) textured stator.

The adhesive force between stator surface and friction material decreased after dimples were fabricated on the stator surface. The cracks attributed to the fatigue still occurred. However, the crack propagation was limited by the texture, as shown in Fig. 13(b). No large sheets of debris were found on the textured surface (Figs. 5 and 8). At the end of the 100-h test, only small wear particles were observed on the surface (Fig. 11(d)). Only a few cracks were observed on friction material, and the material around the cracks was comparatively smooth (Figs. 9(c) and 9(d)). The wear mechanism of friction material sliding against the textured stator changed to a small size fatigue and slight abrasive wear, which explained the decrease in the wear of friction material from 3.8 μm to 1.1 μm in the 100-h test (Fig. 10).

The wear problems of PTFE composites applied in USMs may differ largely from the wear problems of the material applied in normal conditions. One of the differences is that large pieces of transfer film should not be generated because a sufficient amount of friction force is needed to drive the rotor. In this study, a large piece of transfer film was formed during the run-in stage when the smooth stator was used, as shown in Fig. 8. The films were peeled off and replenished, which resulted in a high wear rate of friction material. When the textured stator was employed, the presence of a transfer film decreased remarkably and was replaced by small particles, as shown in Figs. 5 and 8. The underlying cause of this result was that the adhesive force between stator and PTFE composite decreased owing to the laser surface texturing to a value that was less than the cohesive strength of the material. In addition, the ultrasonic vibrations reduced the transfer film tenacity, resulting in the removal of transfer film in both the run-in and steady stages. Thus, if transfer film generation was prevented by laser surface texturing, the wear rate of PTFE composite would have decreased.

In the steady stage, the PTFE composite fatigued under the alternating stress, and then the texture reduced the size of particles, which were peeled off from the composite, by weakening the adhesive force. To conclude, the laser surface texturing can reduce the wear of PTFE composite applied to travelling wave USMs in both the run-in and steady stages, which is experimentally demonstrated in this study.

5 Conclusion

In this paper, the effects of the laser surface texturing on the tribological properties of the textured stator and PTFE-base composite in a USM were studied. The critical findings are concluded as follows:

(1) The speed and efficiency of the USM decreased when the laser texture was fabricated on the stator surface, and the values decreased further with the increase in texture density. The reason is the friction reduction effect of the surface texture. However, after 100 h, the non-load speeds of the textured stator and non-textured stator became very close, and the difference in their maximum efficiencies decreased from 4.7% to 3.7%.

(2) In the run-in wear stage, the generation of a large transfer film of PTFE composite was prevented by laser surface texturing, and the adhesive wear decreased predominantly. Large pieces of adhesive material were not found on the surface of the textured stator, and the form of wear debris changed to particle-like.

(3) In the steady wear stage, the laser surface texturing reduced the size of particles, which were peeled off from the composite, by weakening the adhesive force. The wear mechanisms of friction material were small size fatigue and slight abrasive wear. The wear height of friction material sliding against the non-textured stator was 3.8 μm , and this further decreased to 1.1 μm after the texture was fabricated. This showed that the wear height decreased by approximately 71%.

The generation of large pieces of PTFE composite transfer film was prevented using laser surface texturing, and adhesive wear was reduced notably despite the insignificant decrease in load capacity and efficiency, so that the service life of the motor could be extended. This study introduces a wear reduction method for travelling wave USMs. We believe that the insignificant decrease in load capacity and efficiency does not affect the applications of USMs. Our next study seeks to optimize the design of a texture that can reduce wear and increase motor performance.

Acknowledgements

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