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ORIGINAL ARTICLE

Tribological behaviors of two micro textured surfaces generated by vibrating milling under boundary lubricated sliding

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Abstract Surface texture technology is widely used in various friction pairs to obtain good lubrication. However, ever present researches are mainly focused on regular and simple texture shapes such as dimples and grooves. Few works on complex micro texture have been reported due to preparing difficulty. In this paper, two surfaces with complex micro texture, which are micro scale textured (MST) surface and micro furrow textured (MFT) surface, are prepared by ultrasonic vibration-assisted milling (UVAM) method. Also, their tribological behaviors under starved oil lubrication and reciprocating sliding condition are experimentally investigated with a smooth sample as comparison. Experimental results indicate that although the application of ultrasonic vibration leads to the increase of roughness of MST and MFT surfaces, both the two machined micro textures contribute to the improvement of lubricant film strength, and MFT surface has better tribological performance than that of MST surface. As a result, under test conditions, micro texture formed by UVAM method can greatly improve the tribological property of friction surface, especially for its bearing capacity and wear resistance.

Keywords Surface texture · Friction and wear · Vibration cutting · Ultrasonic vibration

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1 Introduction

According to the traditional theory of tribology, a smoother surface is more capable of reducing friction and resisting wear. However, in recent years, it has been proven by many studies that some non-smooth surfaces with artificially created micro features, which are called textured surfaces, presented better tribological properties than did smooth surface.

The idea of using artificially created micro feature to improve the tribological property of contact interface is originated from the 20th century 60s. Hamilton et al. firstly proposed that bulges created on surface would be beneficial to produce additional hydrodynamic lubrication [1]. Izhak Etsion et al. firstly studied the application of surface texture technology in mechanical seals, and pointed out that micro dimples created on a seal surface with proper size made a great contribution to good sealing property [2]. Considerable studies have been carried out to examine the effects of different texture shapes on the friction and wear behaviors of various surfaces under different lubrication conditions [3–5]. Many studies have shown both analytically and experimentally that surface texture is an effective way to improve surface tribological properties as a result of wear debris trapping, lubricant reserving, and hydrodynamic pressure generating mechanisms [6–8].

The development of surface texture fabricating technique is the key to promote experimental study and practical application of this technology. At present, frequently used surface texture fabricating methods include reactive ion etching (RIE) technique [9], abrasive jet machining (AJM) process [10], LIGA technique [11], and laser surface texturing (LST) technique [12]. RIE can fabricate micro feature with size less than 3 μm, but it is of low selectivity and has the security risk of hazardous gas and radio-frequency power. The material removal mechanism of AJM is the impaction effect of high-speed air flow mingled with fine abrasive particles and, therefore, the geometric accuracy of the created micro feature is

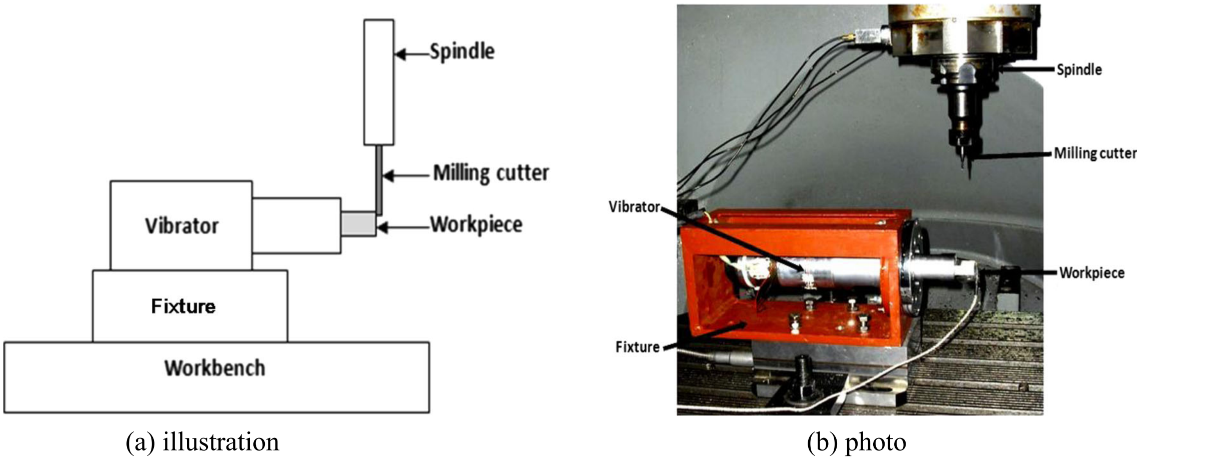


Fig. 1 Fabricating setup. **a** Illustration. **b** Photo

low. The main limitation of lithography technique is the high cost of synchrotron radiation light. LST is the most widely used texture fabricating method for its advantages of rapid processing, high machining accuracy, and clean and non-pollution. However, ablation process in LST may change the microstructure of machined surface.

As discussed above, each texture fabricating method commonly used has its limitation, and all the techniques cannot easily realize the fabrication of complex micro texture shape such as some bionic features. Because of the processing difficulty of complex micro texture shape, present studies are mainly focused on the texture with regular and simple shape, such as dimples and grooves. There have been few reports on the study of complex micro/nano texture shape created artificially.

Ultrasonic vibration-assisted milling (UVAM) process is a combined machining method, in which vibration with a regular frequency in an ultrasonic range is imposed on cutting tool or workpiece. In UVAM, in addition to main motion and feeds motion, high-frequency mechanical vibration is exerted on tool/workpiece, which makes tool path very complicated. As a result of nearly 20,000 times vibration per second, a tremendous number of tool marks are uniformly distributed on the machined surface, and thus surfaces with various regular micro features can be formed [13].

This paper explores the application of UVAM technology in complex micro/nano feature fabrication, and experimentally studies the tribological behaviors of the fabricated surfaces by comparing with a smooth surface.

2 Experimental details

2.1 Sample preparation

The samples were fabricated on a machining center. A designed ultrasonic vibrator, which is connected with the workpiece by threaded connection, was used to produce feed direction mechanical vibration with a 19.58-kHz frequency. Its vibration amplitude ranges from 0 to 20 μm and can be online monitored and controlled via a sensor during cutting process. An illustration and a photo of the fabricating setup are respectively shown in Fig. 1a, b. The workpiece material is aluminum alloy. The cutter used is a two-flute carbide end mill with a diameter of 2 mm.

Three plate samples, 20×18×6 mm in dimension, were fabricated with different processing parameters. Detailed processing conditions, for samples, are listed in Table 1. Here, 0 μm of vibrating amplitude means no ultrasonic vibration was applied, that is, the sample was machined by a conventional milling process.

Figure 2 shows the micrographs of the three samples. Figure 2a shows a smooth sample (SS), with which the other two textured samples can be compared. Figure 2b, c show a micro scale textured (MST) sample and a micro furrow textured (MFT) sample, respectively. The formation of surface with complex micro texture in UVAM is the result of complex cutting movement caused by ultrasonic vibration, and process parameter matching affects the relative tool trajectory and determines the morphology of machined surface. The effect of process parameters matching on roughness of machined surface in UVAM has been investigated in Ref. [13] and will not be elaborated on here.

After fabrication, the three samples were cleaned twice in ultrasonic bath by alcohol and then dried. Three-dimensional

Table 1 Process parameters of plate sample

Parameter	1. Smooth	2. Micro scale textured	3. Micro furrow textured
Spindle speed (rpm)	5000	5000	3000
Feed (mm/min)	40	80	48
Amplitude (μm)	0	10	10

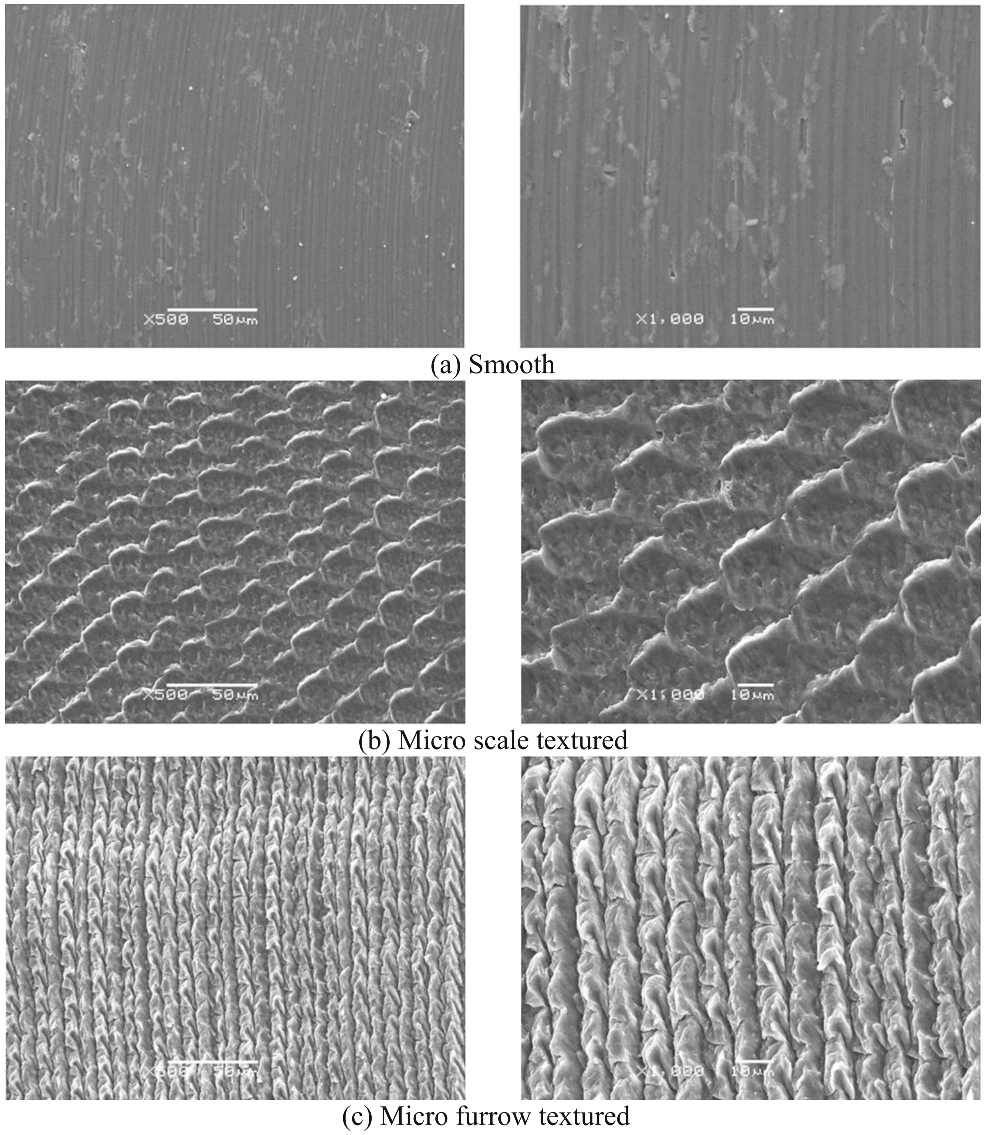


Fig. 2 SEM micrographs of three samples. **a** Smooth. **b** Micro scale textured. **c** Micro furrow textured

surface roughness of the three samples was measured accurately with an optical interferometer. Each surface was measured three times, and their average value was determined as the measuring result. According to measuring result, the surface roughnesses of the three samples are 0.182 μm Ra (SS), 0.326 μm Ra (MST), and 0.417 μm Ra (MFT), respectively.

2.2 Friction and wear test

The purpose of this experiment is to investigate the tribological behaviors of MST and MFT surfaces compared with that of SS surface.

The friction and wear test was conducted with a pin-on-disk tribometer (CETR Corp., USA) under reciprocating sliding condition. The schematic diagram of the test is shown in Fig. 3. The upper specimen is a cold-drawn steel-tapered pin with a hardness of 860 HV. The small end diameter of the pin is 1 mm with surface roughness of 0.04 μm Ra. The lower specimen is the plate sample formed by UVAM. The sample was fixed,

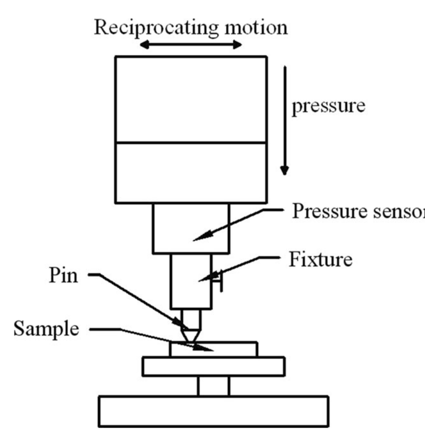
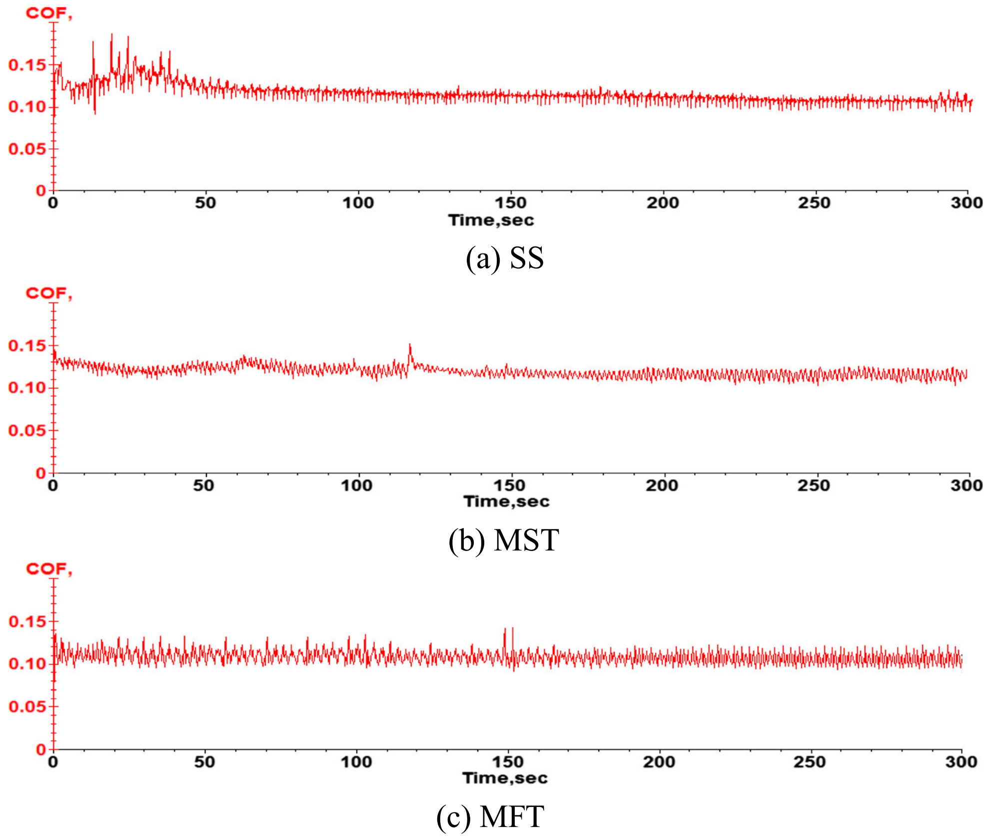


Fig. 3 Schematic diagram of friction and wear test

Fig. 4 The friction coefficient performance of three samples (load=20 N, sliding speed=8 mm/s). **a** SS. **b** MST. **c** MFT



and the pin was reciprocating sliding against the sample. The friction and wear test was conducted under starved oil lubrication condition with calcium-base grease as lubricant. That is, only a certain amount of grease was burnished on sample surface before each test, and no lubricant was added during the test process. The test was performed at room temperature.

Before the test, a 5-min running-in process was conducted for the three samples at a normal load of 10 N, a sliding speed of 6 mm/s, a stroke of 15 mm, and a duration of 10 min. The purpose of the running-in process was to slightly grind off the local crests of MST and MFT surfaces, and thus reduce the influence of surface roughness increase to their friction behaviors. After the running-in process, all the samples were recleaned by acetone and alcohol.

The friction and wear test was carried out with a stroke of 15 mm, a normal load of 20–160 N, a speed of 2–10 mm/s, and a duration of 20 min.

A same new pin was reinstalled when testing a new sample to control experimental error, and the dynamic data of friction coefficient was recorded during the test process for analysis.

The worn surface was observed by scanning electron microscopy. A 3D Super Depth Digital Microscope was used to measure the wear loss.

3 Results and discussion

Figure 4 shows the friction coefficient performances of the three samples at 20 N applied load, 8 mm/s sliding speed, and 5-min duration. It can be seen that there is an about 40-s running-in stage in the initial stage of the test for SS surface, while MST and MFT surfaces do not have. However, there is

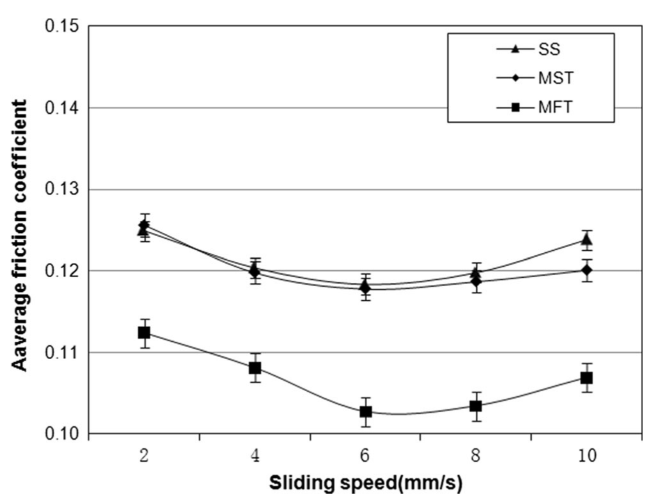


Fig. 5 Friction coefficient performance of three samples at different speed

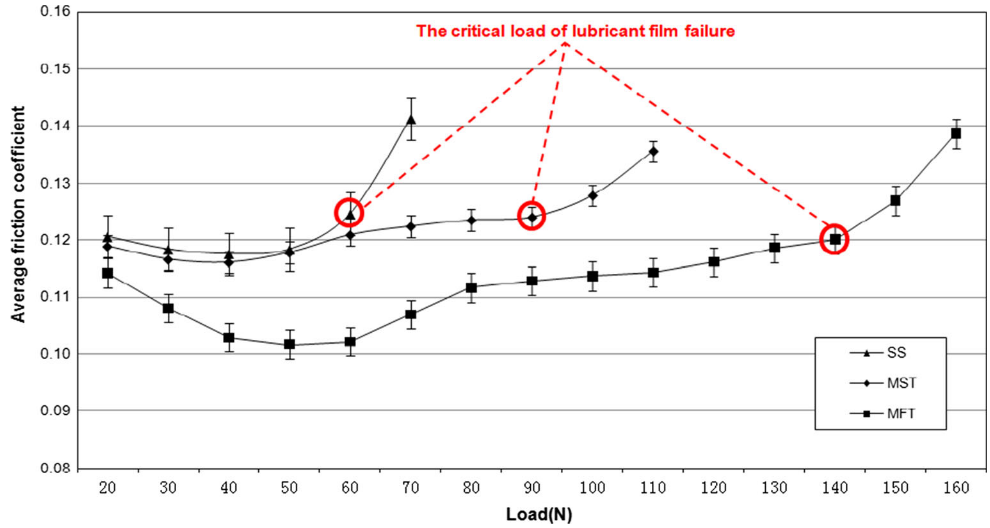


Fig. 6 Friction coefficient performance of three samples at different load

no big difference for the average friction coefficient value among the three samples after they enter steady rubbing state. According to measuring results, the average friction coefficients for the three samples are 0.1193, 0.1189, and 0.1142, and their mean square deviation values for friction coefficient variation are 0.1489, 0.1357, and 0.1939, respectively. Even though MFT surface shows a slightly lower friction coefficient value, the fluctuation of friction coefficient for MFT surface is slightly bigger than those of SS and MST surfaces because of its higher surface roughness. On the whole, the two kinds of micro textures do not exert much influence on friction coefficient under test conditions.

Under boundary lubrication condition, the value of friction coefficient is determined by the roughness of contacting surfaces and lubricant film thickness. On the one hand, micro texture contributes to the improvement of lubricant absorption and reservation capacity of surface; on the other hand, while it leads to the increase of surface roughness. Therefore, for

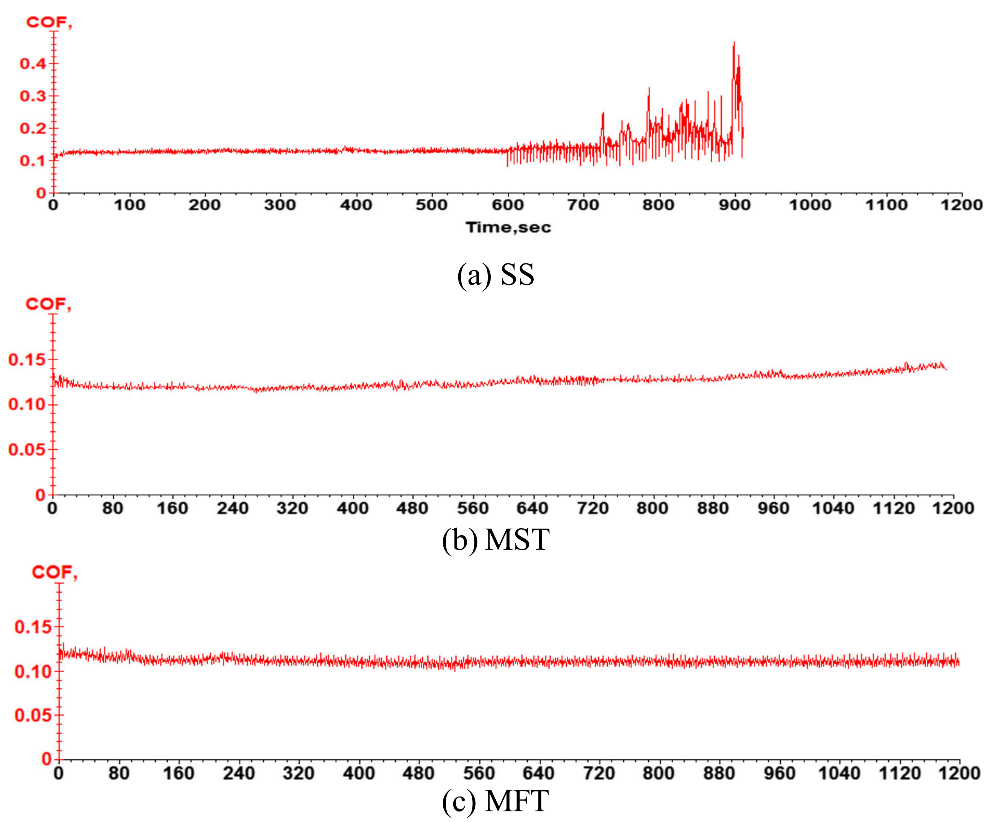


Fig. 7 Friction coefficient for various samples (load=60 N, sliding speed=6 mm/s). **a** SS. **b** MST. **c** MFT

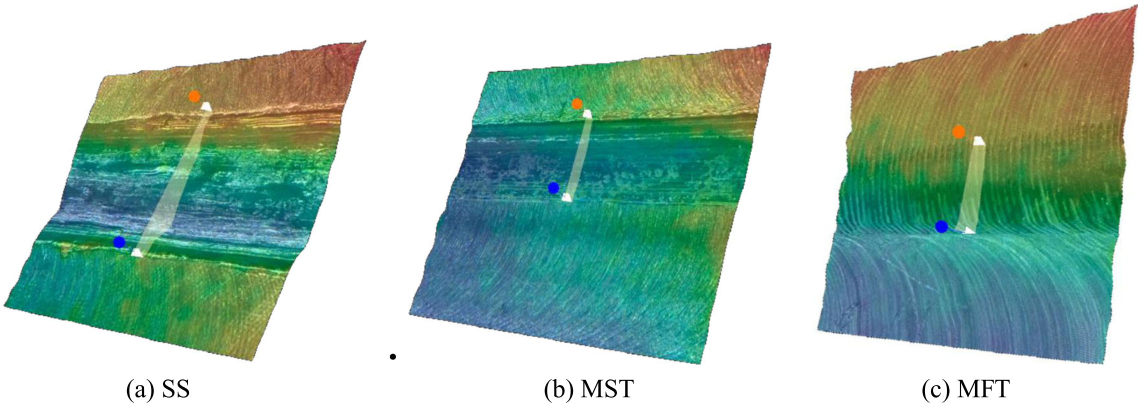


Fig. 8 3D topographies of wear area for tested samples. **a** SS. **b** MST. **c** MFT

contact surfaces working under certain lubrication condition, only micro texture designed properly can help to improve the tribological property.

The influence of sliding speed on friction coefficient performance was investigated as shown in Fig. 5. The test was conducted at a constant load of 40 N, from the lowest sliding speed of 2 mm/s. The sliding speed was increased in a stepwise manner after a 5-min running at each speed, until a maximum speed of 10 mm/s was reached. For all samples, similar trend is observed; friction coefficients are decreased with speed increasing from 2 to 6 mm/s, and then slightly increased with speed increasing from 6 to 10 mm/s, which is consistent with the Stribeck curve. The lowest friction is expected at 6–8 mm/s. Compared with SS and MST surfaces, this kind of variation trend of friction coefficient for MFT surface is more obvious. It is also shown that compared with SS surface, the friction coefficient performance for MST surface does not change too much, while MFT surface shows good friction property especially at a sliding speeds of 6–8 mm/s. The good friction coefficient performance of MFT surface can be attributed to the accumulative lubricant absorption and reservation effect of large amounts of micro furrow texture, and this kind of effect is more obvious at higher sliding speed due to a better fluidity of lubricant. Compared with MFT surface, the micro depth of scale texture on MSF surface is much smaller, the micro scale texture may be gradually ironed out at 40 N applied load, and therefore this accumulative lubrication effect of micro texture is less obvious.

The influence of applied load on friction coefficient was also investigated as shown in Fig. 7. The test that was carried out at a constant sliding speed of 6 mm/s, form the lowest load of 20 N. The load was increased in a stepwise manner with an incremental unit of 10 N after a 5-min running at each load, until a sudden increase for friction coefficient occurred. It can be seen that both MST and MFT surfaces show better friction behavior than does SS surface. For SS surface, the friction coefficient is almost a constant with 20–50 N applied load, and then rapidly increased. For MST surface, the friction coefficient is almost a constant with 20–50 N applied load, slightly increased with 60–90 N applied load, and then rapidly increased with increasing load up to 110 N. For MFT surface, the friction coefficient has an initial tendency of slow decreasing with the load increasing from 20 to 60 N, while an inverse variation trend is seen when the load changes from 60 to 140 N. A sharp rise trend is then observed with the load changing from 140 to 160 N.

The relationship between friction coefficient and applied load for the three samples indicates that there is a clear friction transition around 60 N applied load for SS surface, 90 N for MST surface, and 140 N for MFT surface, which can be seen as the limit load value lubricant film can bear, as indicated in Fig. 6. As a result, under experimental lubrication condition, the two micro textures greatly influence the tribological behavior of the tested sample at large load, and has a positive effect on the maximum bearing capacity of friction surface. Under starved lubrication condition with large load, the

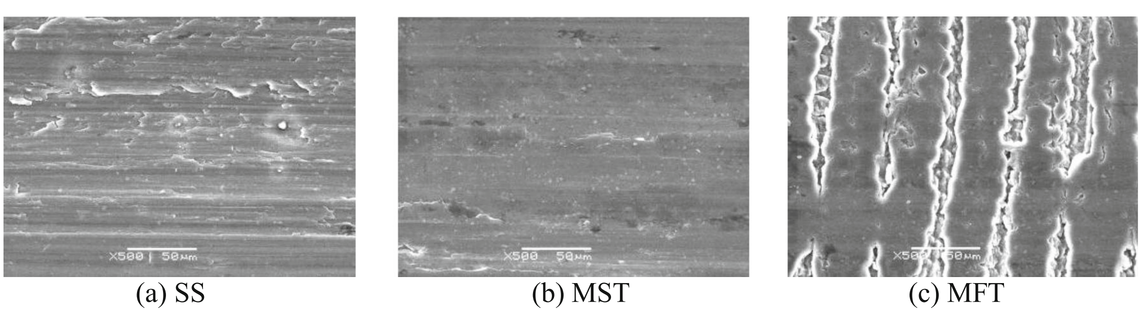


Fig. 9 SEM photos of wear area for tested samples. **a** SS. **b** MST. **c** MFT

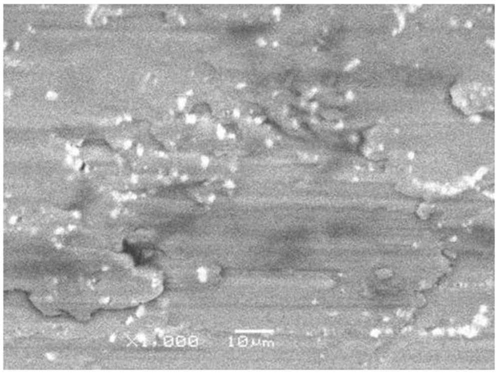


Fig. 10 Backscattering diagram of worn surface for MST

lubricant might be gradually extruded from friction area, and the lubricant film would become more and more thin. In this case, the lubricant absorption and reservation capacity of friction surface play an essential role for its tribological behavior.

The influences of the two studied micro textures on wear resistance of surface were also investigated. The test was conducted at a constant load of 60 N, a constant sliding speed of 6 mm/s, and a duration of 20 min. As test results, the friction coefficients, the 3D features of worn areas, and the SEM micrographs of worn areas for the three samples are respectively shown in Figs. 7, 8, and 9. As seen in Fig. 7a, for SS sample, a clear friction transition occurs after a 10-min steady running process, and the friction coefficient increases quickly after that, until up to more than a value of 0.4. That is, for SS sample, the lubricant film fails after 10 min of running, and the friction interfaces enter into dry friction condition from then on. For SMT surface, as shown in Fig. 7b, the friction coefficient is a constant during the first half of the running process, but there is a very slight growth trend during the second half of the running process. Compared with SS and SMT surfaces, SFT surface experiences a more steady sliding process of 20 min with the friction coefficient remained constant.

According to the friction coefficient performances of the three samples, under starved oil lubrication condition, the two micro textures tested can help to keep the thickness and strength of the lubricant film, especially at larger load and longer rubbing duration.

The 3D topographies and micrographs of worn areas for the tested samples can be observed in Figs. 8 and 9. Table 1 lists the sizes of wear area and wear rates for the three samples. The wear rate is calculated as follows:

$$\varepsilon = V/FL \quad (1)$$

where V is the volume of worn area (mm^3), F is the norm load (N), and L is the sliding distance (m).

As shown in Figs. 8a and 9a, for SS surface, the burnished lubricant had been grinded away; clear abrasive wear and adhesive wear tracks are seen as a result of dry friction mechanism. Figures 8b and 9b show that the micro scale texture had been evened off, with very little abrasive wear track observed. After wear test, the MST surface is cleaned twice in ultrasonic bath by alcohol, and then backscattering analysis is made to analyze surface composition as shown in Fig. 10. Analysis result shows that lubricant component is observed in worn area of MST surface. The reason is that much lubricant can be pressed and absorbed into material interior along the edges of scale texture and the inner micro cracks of mental materials, and thus lubricants can be deeply reserved. It can be seen from Figs. 8c and 9c that the micro furrow texture is not destroyed in 20 min running process, and scarcely any sign of wear and tear can be observed.

According to Table 2, the wear rates of the three samples are 5.346×10^{-5}, 0.561×10^{-5}, and 0.075×10^{-5} mm^3/Nm, respectively. The good wear resistance of MFT surface can be attributed to the proper shape of micro texture and its proper micro size.

Table 2 Measuring and calculating results for wear test

Parameter	1. SS	2. MST	3. MFT
Maximum width of worn area (μm)	526.5	158.7	109.7
Depth of worn area (μm)	102.4	26.0	4.3
Wear rate (10^{-5} mm^3/Nm)	5.346	0.561	0.075

4 Conclusions

In this paper, we fabricated two micro textured surfaces by UVAM method and studied their tribological behaviors under starved oil lubrication and reciprocating sliding condition. Conclusions can be summarized as the following:

(1) Under test conditions, compared with SS surface, the two studied micro textures, which are MST and MFT, do not exert much influence on friction coefficient at low applied load. However, MFT surface shows good tribological performance at larger applied load and larger sliding speed compared with SS and MST surfaces.

(2) Under starved oil lubrication condition, micro texture helps to form stronger lubricant film. According to test results, compared with SS surface, the critical load values for MST and MFT increase by 13 and 50 %, respectively. As a result, proper micro texture by UVAM can significantly improve the maximum bearing capacity of friction surface.

(3) According to test results, the two studied micro textures make brilliant contribution to the improvement of

surface wear resistance. Compared with MST surface, this improvement is more significant for MFT surface.

On the whole, micro texture machined by UVAM method contributes to the improvement of lubricant absorption and reservation capacity of surface, but it also leads to the increase of surface roughness. Therefore, for friction interfaces working under certain lubrication condition, only micro texture with proper shape and micro size can help to effectively improve the tribological property of friction surface. The prediction and optimization for the pattern of micro textured surface by UVAM is one of the most important content in further research.

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