Improving the Antifriction Behaviors of Steel by Hybrid Treatments of MoS_2 and Surface Texture

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Abstract: In the present paper, the composite coatings with MoS_2 and graphite in the epoxy resin were deposited on the textured surface of steel by laser and wire-electrode cutting technology to improve the anti-friction behaviors of the steel. The influences of the content of MoS_2 and graphite and the types of surface texture on the anti-friction behavior were studied systematically. The experimental results show that the textured specimens with 1 mm space line and pentagon shape pore exhibit low friction behaviors under dry friction. CoF (coefficient of friction) of the pore and line textured with high content of MoS_2 and graphite is reduced by 27.7% and 42.3% under dry friction and by 30.0% and 33.3% under starved lubrication, respectively. CoF of the texture and coating duplex-treated steel is much lower than that of the untreated steel due to the solid lubrication of MoS_2 and graphite under dry friction. The possible antifriction and antiwear mechanism is discussed. It is concluded that the duplex-treated steel with the texture and coating exhibits good anti-friction behaviors and the composite coatings with solid lubricant are beneficial to improve the tribological properties of steel under starved and dry friction testing conditions. It is shown that hybrid surface treatment with the texture and solid lubricant coating is an effective way to improve the tribological properties of steel. Solid lubricant coatings deposited on the textured surface can be applied to improve the antifriction behaviors of steel under starved lubrication and dry friction.

Keyword: Surface texture, MoS_2, Graphite, Antifriction behavior.

1. INTRODUCTION

In severe operating environments such as high temperature, high vacuum and high load, effective solid lubricants are essential to reduce the wear and energy loss due to the excessive friction at the contacting interfaces [1-5]. Solid lubricant coatings have been widely used under the starved lubrication and dry friction as they meet the exacting demands of oil-starvation or oil-free environment even dry friction in a wide operating temperature range [6, 7]. Currently, among various solid lubricants, MoS_2 has shown promising tribological characteristics [8-11]. MoS_2 is the most widely used lamellar solid lubricant materials for aero space and used in the movement mechanical parts such as gear and precision bearing applications due to its very low coefficient of friction (CoF) because there is an extremely weak shear force in the direction of the plane parallels within the layers. However, the tribological properties of pure MoS_2 are degraded in humid air, causing an increase in CoF and a decrease in service lifetime [12]. There occurs a chemical reaction with water vapor and oxygen. Thus the steel substrates could be eroded and the lubricant performance deteriorates correspondingly. To overcome this shortcoming, a small amount of doping elements and mixed solid lubricants have been co-deposited to form MoS_2 composite coatings has shown the most significant synergy effect [13]. Graphite has a typical hexagonal close-packed crystal structure. There is comparatively strong covalent bond between each carbon atom and the adjacent one at same level and there is comparatively weak secondary bond between each carbon atom and the one at the adjacent level, which leads to good lubricity. Graphite in the composite coating can be prone to cleavage when the friction effects and it will show interlayer gliding with low coefficient of friction [14-16]. These materials are generally considered solid lubricants. If economy and utility were taken into account, epoxy resin was a good matrix material applying to bonded solid lubricants in the composite coatings for its good adhesive property. Therefore, it may be a feasible way to combine epoxy resin with graphite and MoS_2 for improving the tribological properties of steel [17-19]. Xian *et al*. reported that a synergistic effect was found for the combination of graphite on the tribological performance of epoxy matrix composites, which led to the lowest wear rate and coefficient of friction [20]. Suresha *et al*. found that the wear loss of glass–epoxy composite

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E-ISSN: 2409-9848/23

depended on the weight fraction of graphite [21]. However, the role of solid lubricant in resin/graphite composite is not clear. In this study, MoS_2 and graphite were blended to prepare a series of the epoxy resin composite coatings, and the effect of solid lubricants on the tribological properties of the composite was investigated under starved lubrication and dry friction.

It is well known that wear is unavoidable under starved lubrication and dry friction. Therefore, reduction of the friction and importance of wear-resistance behavior in starved lubrication environment as well as dry friction is necessary for industrial engineering. Incorporating the texture technology could also be effective. Researchers have added textures on the surface of sample according to the stress and strain analysis of contacting region and filled the textures with solid lubricant to further reduce the wear of the surface of sample and buffer the impact [22-26]. Hu *et al* found that hot pressing coating gets CoF as low as 0.05 and long wear life of MoS_2 solid lubricant coating [27]. The size and shape of texture affect the friction and wear performance of friction pairs and an appropriate surface texture can improve obviously the performance of samples. However, the friction mechanisms are rarely discussed under starved lubrication and dry friction.

In this study, the surface textures were designed and manufactured by laser and wire-cutting technology respectively, and then the composited solid lubricant coatings were deposited on the textured surface of steel. The surface texturing is used as the storage of solid lubricant. MoS_2 and graphite as solid lubricants are chosen to form the composite coatings, which are filled into the textured surface on the textured surface of specimen. The coated MoS_2 multi-dimple textured specimens were used. The influence of the solid lubricant content and surface texture type on the tribological properties of steel is investigated under starved lubrication and dry friction conditions.

2. EXPERIMENTS

In the present work, the surface texture was firstly fabricated and then the composite coatings of MoS_2 and graphite in epoxy resin were deposited on the textured surface of the steel. Secondly, the friction and wear tests were carried out to investigate the tribological properties of the treated samples under dry friction and starved lubrication conditions, respectively.

2.1. Specimens

MoS_2 and graphite are used as solid lubricant of the composite coatings. Disc shaped AISI 52100 steel of disc is selected as the substrate of the surface texture and the composite coatings, and the friction counterpart is an AISI 52100 steel ball with 9.525 mm in diameter. The diameter and height of the disc are 30 mm and 5 mm, respectively.

2.2. Fabrication of Surface Texturing

Before surface texturing, all specimens with mirror-like surface was polished by mesh SiC wet papers and diamond pastes. The average surface roughness (R_a) is less than 0.02 μm. The specimens were ultrasonically cleaned in acetone and then dried by a blower. The surface texturing type is circle and linear in shape. The textured surface with the circle shape is fabricated by laser technology and the textured surface with the linearity is fabricated by wire-cutting technology, respectively. The manufacturer and model of wire cutting and laser units are Jiangsu Province Raygo Intelligent Company, DK7732 and Keyence Company, MD-X1500C model, respectively. The process parameters of wire-cutting technology are 1.5 A of working current, 10 μA of pulse duration, 6 μA of pulse interval 6 and 20 mm^2/min of cutting speed, respectively. The diameter and maximum depth of the circle texture are both around 1 mm. The depth of the textured is about 1 mm. The surface roughness of the composite coatings is about 0.4 μm. The depth and diameter of the grooves are 1 mm. The schematic description and characteristic features of the laser texturing surface are presented in Figure **1**. There are three kinds of texturing array (triangles, quadrangle and pentagon) on the surface of specimens. The laser technology was use to produce surface texture by a Nd: YAG laser with a frequency of 8 kHz and pulse duration of 200 ns. Burrs formed surrounding the dimple rim during the operation was gently removed by polishing. The side length of the triangles, quadrangle and pentagon circles is about 0.5 mm and the diameter of circle is about 1 mm. The center distance of two circles is about 2 mm. Line textures were fabricated by wire-cutting technology. The depth and width of line groove are 1 mm. The height of the ridges for the textures in line is about 1 mm. The depth of the holes is also about 1 mm. The surface textures on the steel surface are used for the storage of solid lubricant and wear debris during sliding under starved lubrication and dry friction. Figures **1** and **2** show the arrangement of the surface texturing.

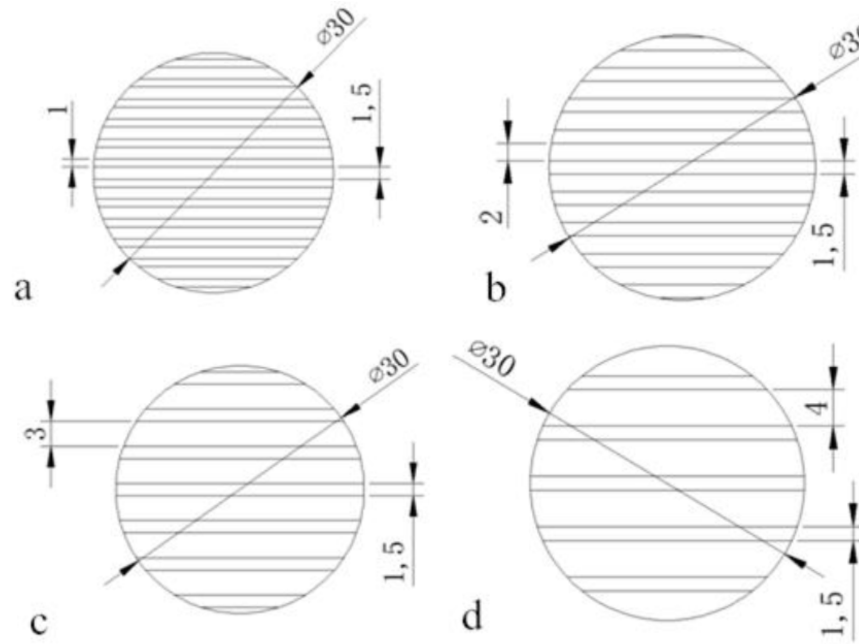


Figure 1: The line textures of different spaces. (**a**) 1 mm, (**b**) 2 mm, (**c**) 3 mm and (**d**) 4 mm.

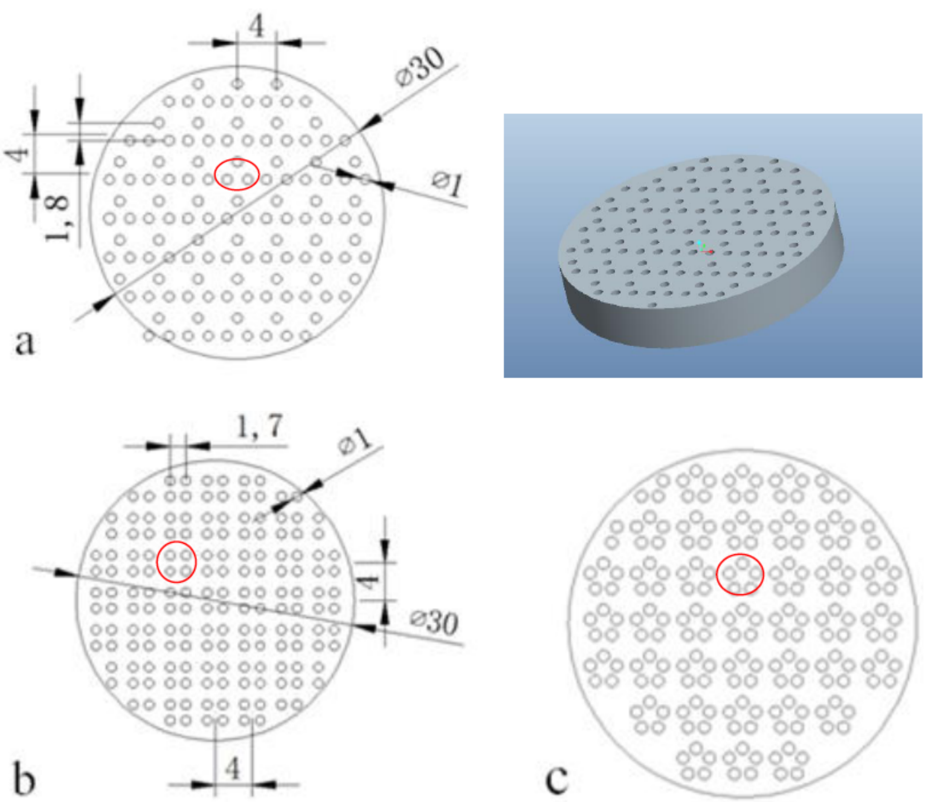


Figure 2: The core texture arrange of samples. (**a**) Triangle, (**b**) Quadrangle and (**c**) Pentagon.

2.3. Preparation of the Composite Coatings

The MoS_2 and graphite coatings were deposited on the textured surface of the specimens and the epoxy resin was used as the composite matrix. MoS_2 powder with an average size of 80 nm and graphite powder with an average size of 5 μm were mixed into the matrix uniformly. Low contents of MoS_2 and graphite powders in the coatings are 14.3% and 4.8% respectively. High contents of MoS_2 and graphite powders in the coatings are 28.6% and 9.6% to investigate the influence of the solid lubricant content on the tribological behavior of the composite coatings. The steel substrates were ultrasonically cleaned in acetone for 10 min, and then dried and cooled down to room temperature, finally the MoS_2 and graphite powders embedded in the epoxy resin matrix were sprayed on the surface of the specimens. The MoS_2 and graphite powders embedded in the epoxy resin matrix were added into beaker and stirred to obtain the uniform mixture for 30 minutes, and sprayed on the textured surface of the specimens by electric paint sprayers. The composite coatings on the textured of steel surface were solidified at the temperature of 120^{o}C for 4 hours in the vacuum drying chamber. The composite coatings on the steel were polished using abrasive paper with 1200$^{\#}$ before the tribotest to reduce their roughness of the composite coatings. The sample surface after coating deposition is uniform because the composite coatings on the textured steel surface were polished after the coating deposition. The thickness of the composite coatings is about 0.5 mm. The roughness of the texted area is larger than that of untextured because there are deep and wide groove in the textured surface of steel. The coating is not thicker than the textured area.

2.4. The Friction and Wear Tests

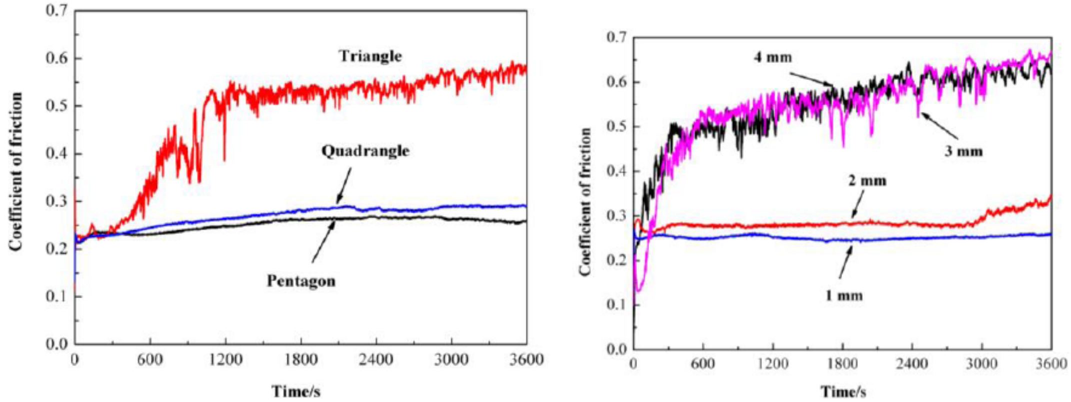
The friction and wear tests of the textured and coated specimens were performed by linear reciprocating ball-on-flat tribometer. The tribological tests have done three times for each sample per friction condition. The steel ball with 9.525 mm in diameter is the stationary specimen and hybrid surface treatment of the textured and coated steel disc is the moving specimens with 30 mm in diameter and 5 mm in thickness. The textured and coated disc was sliding against a ball under starved lubrication and dry friction.

The normal load was 50 N and the frequency was 4 Hz under starved lubrication and dry friction, respectively. The contact pressure was about 1.77 GPa. The displacement was 6 mm. The sliding time was 3600 s. The surface morphology of the specimens by optical microscope after the friction tests under different conditions was observed. The 1000# lubricating oil is used to lubricate the samples. The amounts of lubricant for starvation conditions were calibrated by burette. We have dropped lubricant into the surface of samples, and then scanning the lubricant on the surface slightly, making sure that the film thickness of lubrication between mating surfaces maybe relatively thin and the lubrication condition is in starvation conditions. The sliding direction is perpendicular to the line surface, and the gap is 3 mm, which is smaller than displacement of 6 mm.

3. RESULTS AND DISCUSSION

3.1. Influence of Surface Texture on the Tribological Properties

Figure **3** shows CoF of the textured specimens. Figure **3a** shows CoF of the textured specimens with three different circle textures. CoF of the specimens with the triangle texture increases to about 0.6 with the increase of sliding time. However, CoF of the textured specimens with the pentagon and quadrangle textures is much less and more stable than that of the textured specimen with the triangle texture. CoF of the specimens with the pentagon texture is lower than that of the textured specimens with the quadrangle texture. Therefore, the pentagon array of surface texture is chosen as the arrangement type of the steel for the circle texture. Figure **3b** shows CoF of the specimens with the linear texture, it is found that CoF of the specimens with different interval linear textures is different under the same friction condition. CoF of the textured specimens with linear texture increases with the increase of spaces. CoF of the linear texture with 4 mm interval is as high as 0.65, however, CoF of the linear texture with 1 mm interval is as low as 0.25, therefore, the linear surface texture with 1 mm interval is chosen as the arrangement type of the steel for line texture. The reasons maybe that the densities of the pentagon texture are highest among all the circle textured specimens. The densities of the linear texture with 1 mm space are also highest among all the linear textured specimens. The solid lubricant coatings are filled in the groove on the surface texture to improve the antifriction behaviors of the textured specimens. The friction took place between ball and the surface of the composite coatings, thus CoF was low at the initial stage. With sliding time increasing, the composite coatings on the textured surface were worn gradually and the wear debris increased. For the straight texture with low space, the density of line groove is high, thus the wear debris may be filled into groove, resulting in low friction.



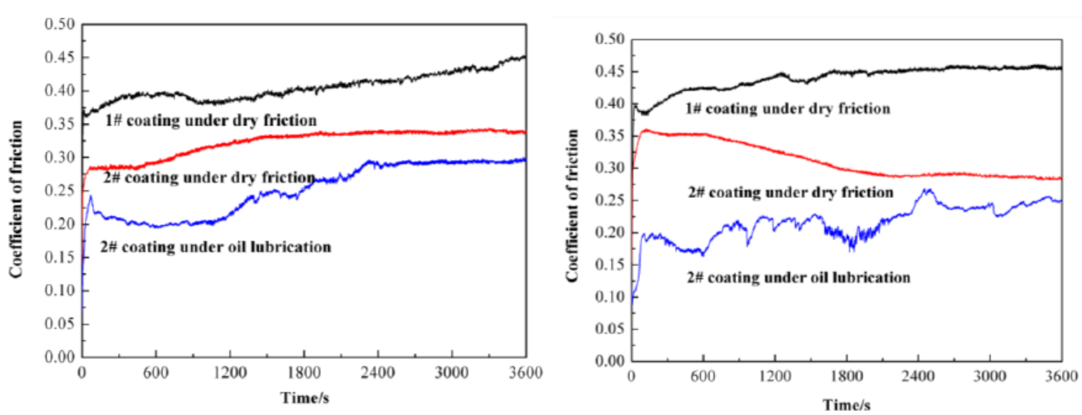
(a) Circle texture under different array textures (b) Line texture

Figure 3: CoF of different textures under dry friction condition.

3.2. Influence of the Content of MoS_2 and Graphite on the Friction Behavior

Figure **4** shows CoF of the circle texture in pentagon array and the line texture with the space of 1 mm of the coated specimen under dry friction and starved lubrication. It is found that CoF of the composite coatings on the specimen surface with high content of solid lubricant coatings (code number is 2#) is lower than that of the composite coatings specimen with low content of solid lubricant (code number is 1#). CoF of the line textured specimen with high content of solid lubricant coatings is also lower than that of the line textured specimen with low content of solid lubricant coatings. For the line textured specimen, the density of groove and hole is higher than that of the circle textured specimen; therefore, the wear debris can be absorbed into the textured surface, resulting in low friction. This means that the line texture seems more suitable for the dry friction condition and starved lubrication.

It is found from the experimental results that CoF of the solid lubricant composite coatings with high content is lower than that of the solid lubricant composite coatings with low content. Under the same friction condition, CoF of the circle textured specimen and line textured specimen of the solid lubricant composite coatings with high content solid lubricant coating reduces by 27.7% and 42.3% respectively. This means that solid lubricant coatings of high content MoS_2 and graphite can improve the antifriction behavior and high wear-resistance performance of the hybrid surface treatment steel. The reason maybe that the thickness of the transfer films on the textured surface increases with the increase of the content of MoS_2 and graphite, which not only reduces the direct contact area but also increases the rolling of wear debris in the contact surface and the sliding space, which makes CoF decrease gradually. Figure **4** also shows that CoF of

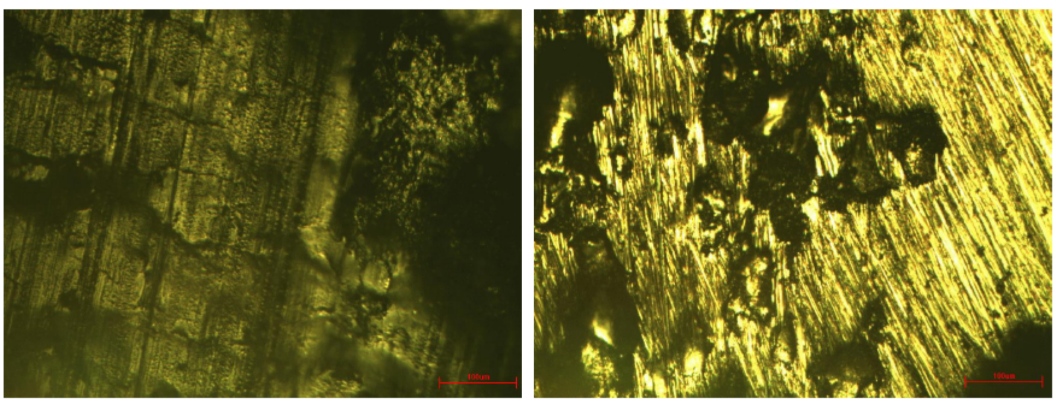


(a) Circle texture in pentagon array (b) Line texture with the space of 1 mm

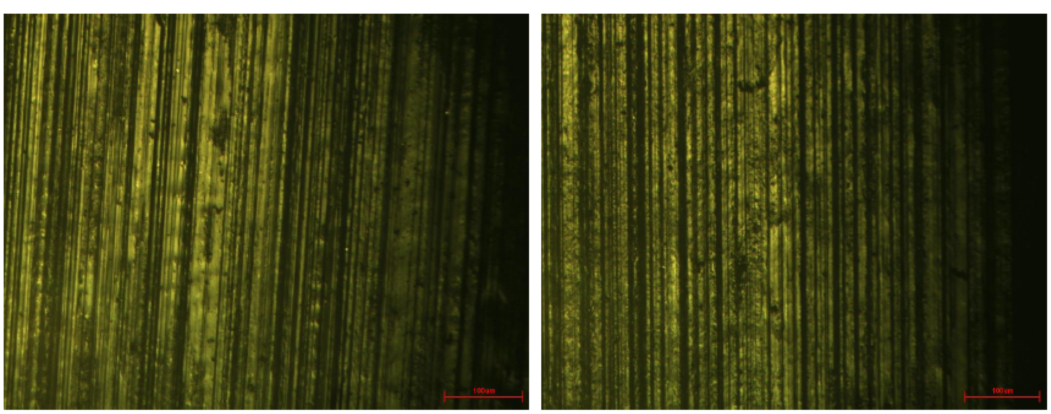
Figure 4: CoF under different the content of solid lubricant and friction conditions.

the circle textured specimen and straight textured specimen reduces by 30.0% and 33.3% respectively when a very thin layer of oil is spread out on the textured surface under the same experimental condition. CoF of the circle texture was stable about 0.2 at the first 20 min and CoF increased to 0.30 in the end. The thin oil film exhibits low-friction and antiwear performance of the composite coating on the circle texture surface, and then CoF increases to close to the value under dry friction. The tendency of CoF is similar with CoF of the end of 30 min of dry friction. This means the friction mainly came from the composite coating at that time and friction is close to the dry friction. The maintaining time about 25 ~30 min of low friction of the line textured coating is longer than that of the circle textured coating. And CoF of the line textured coating is generally lower than that of circle textured coating.

Figure **5** shows the morphology of the worn surface under dry friction and starved lubrication. The worn surface of the specimen was observed by the optical microscope after the friction and wear tests. The results show that there is adhesive wear for the circle textured specimen. The textured surface retains the composite coatings and there are obvious grinding cracks or potholes. This means the composite coatings have a good abrasion resistance for the circle textured specimens. Comparing with these worn images, high content MoS_2 and graphite composite coatings can improve the abrasion resistance of the specimens. There are two aspects influencing the lubrication behaviors on the abrasion resistance of the textured surface: 1) The interface stress concentration of the textured surface become strong with the increase of the lubricant content, thus the lubrication can reduce the abrasion resistance of the surface; 2) CoF of the textured surface reduces after filling the lubricant on which improves the abrasion resistance of the texture surface relatively. The texture surface contains plenty of MoS_2 coating and abrasion of the texture was hardly found on frictional part with the oil film after the frictional experiment. It indicates that the oil film can improve the frictional and antiwear performance and keep the performance for about 20~30 min.

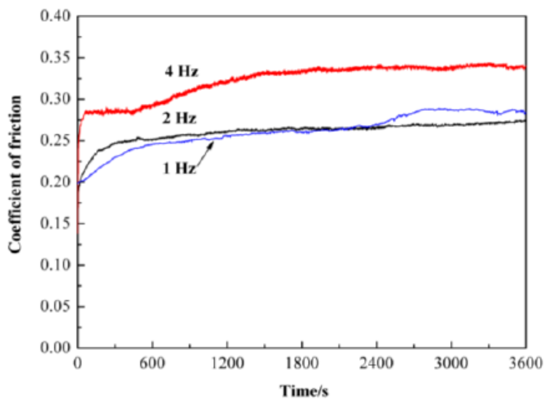


(a) $1^{\#}$ coating on the circle textured surface (b) $1^{\#}$ coating on the line textured surface

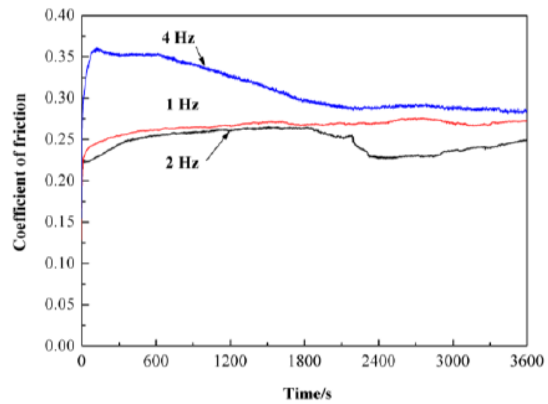


(c) $2^{\#}$ coating on the circle textured surface (d) $2^{\#}$ coating on the line textured surface

Figure 5: Optical image of the worn surface under different friction conditions.



(a) Circle texture



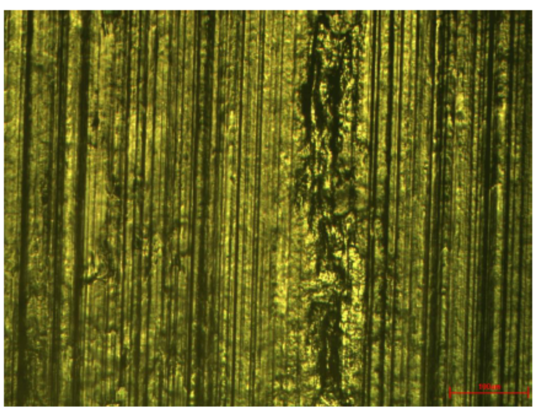
(b) Line texture

Figure 6: CoF under different frequencies.

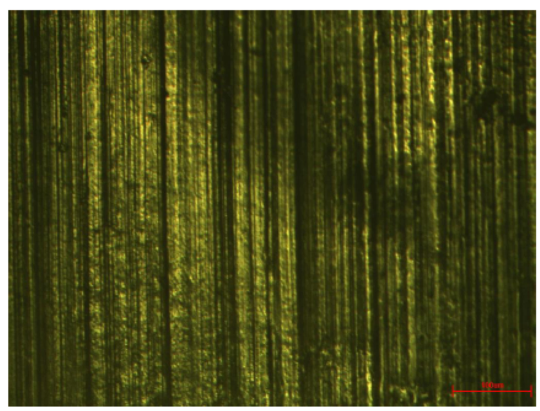
The low-friction and antiwear performance of line texture coating was better than pore texture coating. Applying to industrial production, oil film processing can protect the important instruments for a certain period of time to reduce the abrasion of instruments.

3.3. Influence of Friction Parameters on the Tribological Performance

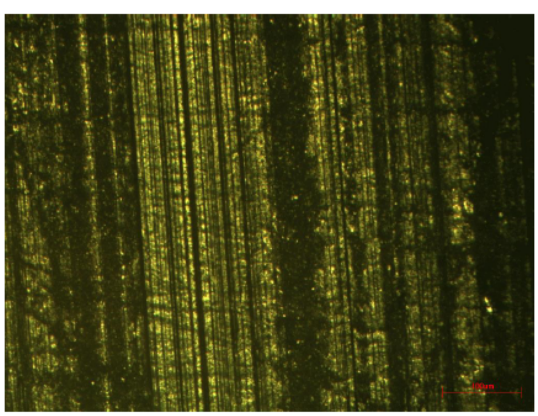
The friction conditions affect strongly the tribological properties of the friction pair. Figure **6** shows CoF of the textured surface under different frequencies (4 Hz, 2 Hz and 1 Hz) and dry friction. Figure **7** shows the



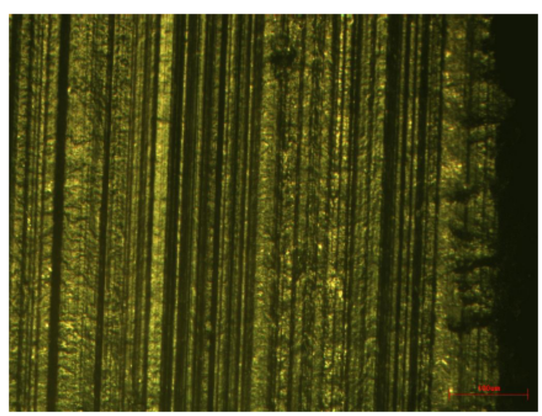
(a) 2 Hz on the circle textured surface



(b) 2 Hz on the straight textured surface



(c) 1 Hz on the circle textured surface



(d) 1 Hz on the straight textured surface

Figure 7: Optical image of the worn surface of 2# coating under different frequencies.

worn surface images of the surface texture of 2# composite coating at the frequency of 2 Hz. It is found that the frequency affects obviously the antifriction behaviors of the textured steel surface. The composite coating with high content solid lubricant exhibits excellent antifriction and antiwear performance. From the experimental results, it is necessary to form a thin layer of films on the textured surface. The thickness of the composite coatings was about 1 mm on the textured surface. It indicates that CoF is low at the initial stage and then increases with the increase of sliding time for the circle textured specimen. And CoF increases at the initial stage and keeps stable with the increase of frequency. Therefore, CoF is lowest at 2 Hz of frequency. It indicates that CoF increase abruptly to high value at the initial stage and then decreases slightly with the increase of sliding time for the straight textured specimen. CoF of the line textured specimen is relatively low under dry friction. The friction and wear behaviors of the straight textured specimen are better than that of the circle textured specimen at the frequency of 4 Hz under dry friction. The friction and wear behaviors of the line textured specimen are almost close to that of the circle textured specimen at the frequency of 1 Hz. However, the friction and wear behaviors of the line textured specimen is as half as that of the circle textured specimen at the frequency of 4 Hz.

The recent researches have suggested that by coupling some solid lubricants with surface texturing on the surfaces of steel [28-37]. Solid lubricants are considered to be any solid material that reduces the friction and mechanical interactions between surfaces in relative motion against the action of a load. Solid lubricants such as MoS_2 and graphite are deposited as an overlayer film on a steel surface, which is one of effective ways by reducing the shear stress at a sliding condition. Surface texturing is another useful way to reduce the friction and wear by the reduction of tribological contact area, storage of abrasive dusts, as well as lubricants preservation capability. Surface texture treatment allows to increase the amount of solid lubricant powder in the dimples and to supply solid lubricant to interface. Moreover, surface texturing can improve the bond strength of the coatings. The combination of surface texture and coatings on the steel provides the low friction and reduces the abrasive wear. The experimental results confirmed that surface texture and the solid lubricant composite coatings had a potential for reducing friction and wear of the steel under starved lubrication and dry friction if the dimples type is appropriate and the solid lubricant content of the composite coatings is suitable. In this study, seven kinds of surface texturing are fabricated on the surface of steel specimen. There are triangles, quadrangle and pentagon array in circle texture and line texture with different distances. It has been proved that a particular texture was beneficial to decrease friction. It is found that the optimum type of surface texture is line texture and high content of solid lubricant is beneficial to low friction under dry friction and starved lubrication. The reduction of the contact area between the frictional couples by surface texturing may contribute to reducing the friction and wear of coating surfaces. On one hand, the surface textures could increase the adhesion strength of film-substrate and then delay invalidation of the solid lubricant composite coatings. On the other hand, the solid lubricants could be stored in the grooves and transferred to the surface after the initial films were run out. The reduction in CoF was found to depend on the elemental composition of the solid lubricant overlayer. Stored in the dimples solid lubricant can be released to the interface and thus increase the longevity of the textured surfaces. This could be explained by high contents of solid lubricants enhanced film wear life. The experimental results showed that there is an improvement in the antifriction performance of the line texture and the circle texture also provided a slight improvement. Moreover, the antifriction behavior of the line texture is stable and the line texture is easily fabricated comparing with the circle texture. Therefore, the line texture is selected as the appropriate type of surface texture, which is also suitable for the industrial application according to the tribotest results and the manufacture method because fabrication of line texture is not expensive technology. The samples with quadrangle and pentagon textures and line texture with 1 mm and 2 mm presents a stable and low friction coefficient. For high texture coverage of the textured samples, there was a run-in stage followed by a stable friction coefficient stage. This phenomenon is attributed to the stress concentration caused by surface profile fluctuation and sharp corners of grid grooves. The samples with high texture coverage have a high surface profile fluctuation. The variation of the antifriction behavior of the textured steel with the composite coatings was thought to be due to the competition between the function of wear debris reservoirs and contact pressure of the friction pair. One of important role of the texture is used as the debris reservoir. The lubricant oil could be stored in the texture and maybe separate the contact surface during sliding. The dimples could also trap wear debris and thus reduced the friction. If the texture space or the dimple density was too high, the texture was easily filled by lubricant oil wear debris under dry friction and starved lubrication, leading to an increase in CoF although the solid lubricant coating generally have low friction. The textured surfaces coated by MoS_2 and graphite have shown to be successful in dry friction and starved lubrication tests. The composite of high content MoS_2 and graphite could provide solid lubricant, resulting in low friction. The results suggest that retaining low and stable friction steel and a coated surface requires the formation of tribofilm on the steel surface or of the presence of lubricant within the contact zone. Based on these results it may be concluded that low friction of the composite coatings on the textured surfaces is mainly determined by storing wear debris in the dimples and the excellent tribological properties of solid lubricant.

4. CONCLUSIONS

1) The composite coatings of MoS_2 and graphite improve effectively the antifriction and antiwear behaviors of the textured steel surface.

2) CoF of the pore texture and line texture surface is reduced by 27.7% and 42.3% for high content of MoS_2 and graphite.

3) CoF of pore texture and line texture is reduced by 30.0% and 33.3% comparing with CoF of dry friction condition.

4) Low friction behavior at the starved lubrication and dry friction is determined by high texture coverage of the textured surfaces, storing wear debris in the dimples and the excellent tribological properties of solid lubricant.

ACKNOWLEDGEMENTS

We acknowledge the financial support from the Natural Science Basic Research Plan in Shaanxi Province of China (2022JM-251).

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Received on 27-04-2023 Accepted on 12-06-2023 Published on 22-06-2023

DOI: https://doi.org/10.31875/2409-9848.2023.10.11