Effect of textured DLC coatings on tribological properties of titanium alloy under grease lubrication

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Abstract
To improve the tribological properties of titanium alloy surface and promote the functional application of titanium alloy, the synergistic anti-friction and wear-resistant effect of laser micro-textures and diamond-like carbon (DLC) coatings on titanium alloy surface under grease lubrication were investigated in this paper. Micro-textures and DLC coatings were fabricated on the surface of titanium alloy by Nd:YAG laser and magnetron sputtering technology. Effects of different surface treatment methods and micro-textures parameters on tribological properties of titanium alloy samples was studied. The results showed that, compared with the smooth titanium alloy sample, the friction coefficient of micro-textured sample, DLC coated sample and textured DLC coated sample decreased by 43.7%, 75.8%, 80.6% respectively. The surface of textured coated titanium alloy had the best tribological properties with a friction coefficient of 0.0799. The wear on the surface of the titanium alloy sample treated by laser micro-textures and DLC coatings was obviously improved. Compared with the severe adhesive wear on the surface of the titanium alloy sample, the surface of the textured coated titanium alloy sample was slightly scratched, and the wear volume was decreased by 97.5%. Meanwhile, DLC coatings with 30% textures density and 20 μm textures depth showed the best anti-friction effect as well as the optimal hydrodynamic lubrication effect. Under the condition of grease lubrication, the surface of textured DLC coated titanium alloy substrate presented favorable anti-friction and wear-resistance effects, which revealed that reasonable micro-textures density and depth could more effectively exert the lubricating and anti-friction properties of textured DLC coatings.

1. Introduction
Titanium alloy, as a kind of high-quality and high-strength structural material, has the advantages of low density, high specific strength, corrosion resistance and outstanding biocompatibility. It is considered as the most attractive material in many industrial fields. Titanium alloy is widely applied in aerospace, medical and marine engineering fields due to its unique comprehensive properties \cite{1–3}. However, the application of titanium alloy in aerospace bearings, artificial joints and ship transmission components is severely limited by poor tribological properties, high and unstable friction coefficient, severe adhesive wear and insufficient protective effect of surface oxide layer on itself. As a result, it is of considerable significance to improve the tribological properties of titanium alloys \cite{4–7}. In recent years, with the development of various surface modification measurements, surface textures technology and surface coatings technology have become research highlights as effective methods to improve the friction and wear properties of mechanical surfaces \cite{8, 9}, providing new methods to effectively enhance the tribological properties of titanium alloy surfaces.

The surface textures possesses specific structure with the capability of storing lubricating oil and collecting wear debris, which is a key factor to improve the tribological performance of the friction pair surface \cite{10}. Fabrication methods of micro-textures typically include mechanical processing, plasma etching, chemical etching and laser processing. Laser processing is widely performed due to its advantages of high versatility, fast
adaptability, high precision and eco-friendliness [11–13]. Dawit et al fabricated textured surface with various combinations of shapes on samples. Compared with non-textured sample, friction coefficient of textured sample effectively decreased [14]. Xijun Hua et al used Nd:YAG solid-state laser and SPI fiber laser to fabricate micro-textures with different morphology parameters on GCr15 bearing steel for further investigation of friction and wear properties. The results showed that, compared with the smooth sample, the friction coefficient of micro-dimples textured sample and micro-bulges textured sample decreased by 38% and 25% respectively [15, 16]. Wieslaw et al fabricated circular micro-textures on the surface of cylinder liner via laser processing. Comparison of tribological behavior of textured and non-textured cylinder liner with reciprocating friction tester showed that the optimal tribological performance was obtained, when the textures density was 13%, the textures depth was 5 μm and the diameter range was 0.15–0.2 mm [17]. Zu Wu et al studied the tribological properties of titanium alloy surfaces and textured titanium alloy surfaces under dry sliding conditions. The results showed that the surface friction coefficient of textured titanium alloy is about 0.5, which is 0.07 lower than that of the titanium alloy [18].

Diamond-like carbon (DLC) coatings is widely used for corrosion resistance and wear resistance due to its advantages of high hardness, large elastic modulus, low friction coefficient and excellent wear resistance [19]. Halim et al deposited DLC coatings on untreated and plasma nitride low alloy steel samples by physical vapor deposition (PVD). Reciprocating test revealed that DLC coated sample formed transfer films between sliding contact surfaces, which decreased friction coefficient and significantly enhanced wear resistance [20]. Song Wang et al studied the tribological behavior of diamond-like carbon coatings on the surface of titanium alloy substrate under high-temperature conditions. The results of which showed that the friction coefficient of titanium alloy surface coated with DLC coatings was lower than that of smooth titanium alloy surface [21]. However, the application of DLC coatings on titanium alloy is limited by large internal stress and low bonding strength when the diamond-like carbon coatings deposited on the titanium alloy matrix [21–23]. In summary, effects of micro-textures or coatings on the tribological properties of titanium alloy is shown in table 1.

Meanwhile, lubricating grease is widely applied in aerospace, marine engineering and other fields due to its advantages of strong sealing performance, low leakage and long operation life. In order to further improve the grease lubrication performance of the titanium alloy surface under complex working conditions, Nd:YAG laser equipment and nano-composite coatings equipment were performed to the fabrication of micro-textures with characteristic morphological parameters and DLC coatings on the titanium alloy surface. Effects of different surface treatments on the friction and wear properties of titanium alloy surface under grease lubrication were studied, and effects of micro-textures depth and density on the anti-friction effect of the DLC coatings surface were investigated. It provides theoretical guidance for further engineering application of titanium alloy.

### 2. Experiment

#### 2.1. Specimen preparation

TC11 (Ti-6Al-3.5Mo-1.8Zr) alloy and GCr15 bearing steel were respectively selected as base material and counter-grinding part. Titanium alloy and GCr15 steel were processed into φ50 mm × 86 mm discs and Φ6 mm × δ10 mm cylindrical pins respectively and then buffed to mirror surface with 400#, 600#, 800#, 1000# and 1200# sandpaper in turn. The titanium alloy disk was ultrasonically cleaned in absolute ethyl alcohol for 15 min, and dried in a pre-vacuum dryer for about 20 min. After pretreatment, some titanium alloy samples were processed by Nd:YAG laser processing system and nano-composite coatings equipment (PLATIT π300, Switzerland) to prepare four different samples: 1. smooth titanium alloy sample (SS); 2. textured titanium alloy sample (TS); 3. DLC coated sample (DS); 4. textured DLC coated sample (TD), as shown in figure 1 (The micro-textures morphology is micro-dimples, the textures parameters of TS and TD are 90 μm in diameter, 20 μm in depth and 30% in density).

Micro-dimples were fabricated on the surface of titanium alloy by laser processing at the same point interval for many times [24]. Specific process parameters are 6.52 W in pulse power, 75 KHz in frequency, 5–7 times in pulse repetition times.

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**Table 1. Friction and wear characteristics of different samples surfaces.**

| References         | Sample                      | Friction value | Wear modes                        |
|--------------------|-----------------------------|----------------|-----------------------------------|
| Zu Wu [18]         | titanium alloy              | 0.57           | deep plow, adhesive wear, plastic deformation |
| Zu Wu [18]         | textured titanium alloy     | 0.5            | plastic deformation               |
| Song Wang [21]     | DLC coated titanium alloy   | 0.108          | slight adhesive wear              |
All samples were polished by polishing machine, ultrasonically cleaned in absolute ethyl alcohol for 15 min and dried in a vacuum oven for 20 min before DLC coatings was deposited. Mechanical pump was turned on and the air pressure in furnace chamber was stabilized at $5 \times 10^3$ Pa. Sample surface was radiated and stabilized at 450°C by heater. Rotation speed of the fixture in the furnace chamber was set to be 3 r min$^{-1}$. 99.99% high-purity graphite target was performed as the sputtering target with deposition period of 150 min. DLC coatings was deposited on the surface of textured samples and smooth samples by magnetron sputtering (table 2). Thickness and hardness of coatings were shown in table 3. Reference can be checked for more technical details on deposition of DLC coatings [25].

### 3. Friction and wear test

Before the test, all samples were polished and ultrasonic cleaned for 15 min. Lower sample was put into the die with the positioning plate locked later. Lithium grease (SKF LGMT2 /1, Switzerland) was poured into the area enclosed by the surface of the lower sample and the positioning plate. As shown in figure 2, the layer of grease was scraped with a scraper to ensure that the surface of each sample was evenly coated with 1.5 mm thick grease, as shown in figure 2. Friction and wear test with pin-on-disk mode was carried out by a multi-functional friction

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Table 2. Textured coated titanium alloy samples.

| Sample | Diameter | Depth | Density |
|--------|----------|-------|---------|
| A1     | 90 μm    | 20 μm | 10%     |
| A2     | 90 μm    | 20 μm | 20%     |
| A3     | 90 μm    | 20 μm | 30%     |
| A4     | 90 μm    | 20 μm | 40%     |
| A5     | 90 μm    | 20 μm | 50%     |
| D1     | 90 μm    | 4 μm  | 30%     |
| D2     | 90 μm    | 12 μm | 30%     |
| D3     | 90 μm    | 20 μm | 30%     |
| D4     | 90 μm    | 28 μm | 30%     |
| D5     | 90 μm    | 36 μm | 30%     |

Table 3. DLC coatings properties.

| Substrate | Coatings | Thickness | Hardness |
|-----------|----------|-----------|----------|
| TC11      | DLC      | 3 ± 0.4 μm| HV2500   |

Figure 1 Schematic diagram of different treatment methods for TC11 surface.
and wear tester (MFT-5000, USA) with the following working conditions: load 30 N, rotation speed 100RPM, rotation radius 20 mm, single duration 15 min, temperature 25 ± 0.5 °C, humidity 40 ± 0.2%. Lower sample coated with grease and upper sample are fixed on a multi-functional friction and wear tester where lower sample rotated counterclockwise as shown in Figure 3. The friction coefficient was continuously measured by the sensors on the friction and wear tester. Wear morphology of the sample surface was observed by the Nano Focus μsurf explorer portable non-contact optical confocal microscope manufactured by Nano Focus Company. Test result was analyzed with the variation of friction coefficient.

4. Results and discussion

4.1. Characteristics of samples surfaces

The confocal microscope, the field emission scanning electron microscope (JSM-7800F) produced by Japan Electronics Co., Ltd (JEOL) and the x-ray spectrometer produced by EDAX Company of the United States were performed to analyze the surface morphology and composition of samples. As shown in figure 4(a), main components of the polished SS surface are Ti, Al and Mo elements which were measured by the line scanning method. Figures 4(b) and 5(a) show the surface of SS deposited with DLC coatings, the thickness of which is 2.9 μm with severe surface roughness. Main component of DS is element C. TS is shown in figure 4(c) (after polishing) and figure 5(b). Owing to the influence of the thermal effect of laser processing, the material in the
molten pool is melted and recast to form a micro-convex platform at the edge of the micro-dimples [26]. The surface roughness of unpolished TS is high as shown in figure 5(b), and the textures parameters are 112 μm in diameter and 25 μm. TD is shown in figures 4(d) and 5(c), the polished TD surface has a lower roughness than the unpolished DS surface. The micro convex platform around the micro-dimples is completely covered by DLC coatings, thus improving the surface quality of TD. The thickness of the DLC coatings on the edge and the bottom of micro-textures is 3.1 μm and 3.1 μm respectively. The diameter of micro-dimples is slightly decreased (the measured diameter and depth are 84 μm and 16 μm respectively) on account of coatings which is completely deposited into the micro-dimples. Besides, the overall structure of micro-dimples is retained. Simultaneously, DLC coatings and textured titanium alloy surface are in contact with each other to generate mechanical engagement, and tangential resistance of engagement points increases friction force of relative movement between coatings and substrate. Which could improve the shear resistance and peel strength of DLC coatings on the substrate surface.

4.2. Effect of surface treatment methods on tribological properties of titanium alloy

Figure 6 showed the influence of different surface treatment methods on the friction coefficient curve of TC11 substrate surface. It can be observed from figures 6(a) and (b) that the friction coefficient of SS fluctuated violently, which was much higher than that of the other three groups of samples. This could be attributed to the
fact that grease on SS surface was rapidly squeezed out of the contact area of friction pair without subsequent supplement during the friction process and cannot form continuous lubricating film, which resulted in the transformation of the lubricating state from mixed lubrication to boundary lubrication or dry friction. With the test progressed, the wear of SS surface intensified as the friction coefficient fluctuated sharply due to the low hardness and poor wear resistance of titanium alloy. The friction coefficient of TS treated by laser microtextures was obviously decreased and average friction coefficient was 0.2320, which was 43.7% lower than that of SS, and the fluctuation was relatively stable. This was because the lubricating grease could be stored in micro-dimples, which ensured that lubricating grease in the friction contact area could be replenished opportunely. Besides, a layer of continuous lubricating film was formed on the contact surface to produce ‘secondary lubrication’. DS with DLC coatings also presented excellent tribological properties. The friction curve maintained stability during the test, and the average friction coefficient was only 0.0996, which was 75.8% lower than that of SS. It could be attributed to DLC coatings with the characteristic of lower friction coefficient. According to the graphitization-transfer film theory, a certain energy barrier could be overcome by the metastable carbon which could be transformed into graphite with stable structure inside DLC coatings [27]. Free graphite is mixed with lubricating grease on the friction contact surface to form a continuous lubricating transfer film for reduction of friction coefficient. However, the friction coefficient of DS showed a gradual upward trend after 200 s, which may be explained with the fact that the lubrication transfer film hardly stayed on the contact.
surface and was gradually squeezed out due to the uniform and smooth surface of DLC coatings. Resulted in gradual decrease of the lubrication transfer film and increased in the friction coefficient. Average friction coefficient of TD, which showed the minimal friction coefficient, was only 0.0799, which was 80.6% lower than SS, 65.6% lower than TS and 19.8% lower than DS. This was because synergistic effect of friction-reducing and lubricating could be made by micro-textures and DLC coatings. Although it has been mentioned above that micro-textures morphology parameters of textured surface on which DLC coatings was deposited were slightly decreased, the function of micro-textures storage lubricant and capturing abrasive particles can still be exhibited. By capturing free graphite formed in the graphitization process and lubricating grease to form a high-efficiency lubricant, the friction properties of TC11 surface could be significantly improved by formation of solid-liquid lubricating film. Although friction coefficient of TD fluctuates slightly after 500 s due to the gradual consumption of high-efficiency lubricant in micro-textures, the overall friction coefficient of TD is still lower than that of the other three samples.

Wear morphology, cross-sectional profile and wear volume on the surfaces of SS, DS, TS and TD were shown in figures 7 and 8. It can be clearly seen from figure 7(a) that severe furrow and adhesion scar are on the surface of SS. This was because the surface of titanium alloy in contact with GCr15 steel was broken and torn with adhesion scar, and further flaked off with metal particles during the test. The particles remaining on the contact surface function as the third body [28], continuously plowed the contact surface under the load and led to furrow and three-body abrasive wear, which resulted in sharp fluctuation in friction coefficient. This was consistent with the phenomenon observed in figure 6(a). As shown in figure 7(b), compared to SS, the wear morphology of TS surface was improved as the wear volume is decreased by 68.2% (figure 8). Only the micro-convex platform around micro-textures on the TS surface was smoothed out and micro-textures are plastically deformed from circular to oval. Besides, there was no obvious wear scar on the surface of TS, which could be attributed to that micro-textures can store lubricant and collect abrasive particles, improve the lubrication conditions in the friction area, and avoid secondary wear caused by metal particles. In figure 7(c), slight wear can be observed on the surface of DS, the wear volume was decreased by 93.7% compared to SS, and the roughness of wear scar area was lower than that of other area due to characteristics of low friction coefficient and high hardness of DLC coatings. During the test process, scratch was generated with adhesive wear on the upper sample. The shear of adhesive wear mainly occurred in the shallow surface layer of the softer upper sample, micro-pores and low-lying areas on the DS surface were evenly filled with soft metal, which made the surface of wear trace area relatively smooth. Compared with other samples, the surface of TD presented only slight wear scratch on the surface and no obvious abrasion scar was found, as shown in figure 7(d). It can be seen from figure 8 that the wear volume of the TD was decreased by 97.5% compared to the SS. It was proved that the composite lubrication surface structure with surface micro-textures and DLC coatings provided favorable lubrication and wear resistance, effectively protected the surface of TC11 titanium alloy substrate, improved the lubrication effect on the friction area and decreased the wear of abrasive dust on the contact surface during the wear process. Compared with SS, DS and TS surface, the anti-friction and anti-wear effect of TD surface was obviously optimal under the same test conditions.
4.3. Effect of textures parameters on friction properties of DLC coatings

In order to further investigate the influence of micro-textures parameters on the friction performance of DLC coatings on titanium alloy surface, the variation curve of DLC coated surface friction coefficient and the average value of friction coefficient in stable phase under different textures density/depth were respectively shown in

![Figure 7. Wear morphology and cross-sectional profile of samples with different surface treatments (a) SS (b) TS (c) DS (d) TD.](image-url)
Figure 8. Wear volume of samples with different surface treatments.

Figure 9. Friction coefficient of samples with different texture density (a) friction coefficient curve (b) average value of friction coefficient.

Figure 10. Surface friction performance of samples with different texture depth (a) friction coefficient curve (b) average value of friction coefficient.
As can be seen from figure 9(a), during the stable wear period, the friction coefficient of A1 and A2 increased rapidly and showed severe fluctuation. It is supposed to note that A1 possessed the highest friction coefficient. In contrast, A4 and A5 entered the stable wear period quickly with stable friction coefficient and no obvious fluctuation. The curve of A3 showed certain fluctuation with the optimal friction coefficient in the test. The effect of surface textures with different densities can also be clearly seen from figure 9(b). Under grease lubrication, the average friction coefficient of the surface of textured coatings of titanium alloy exhibited 'inverted-volcano-type' relationship with the increase of textures density. The surface friction coefficient of A3 was the lowest, and decreases by 45%, 27%, 17% and 30% respectively compared with the surface friction coefficient of A1, A2, A4 and A5, which can be proved that the surface friction performance of textured coatings with textures density of 30% (A3) presented the optimal frictional properties within the scope of this study. The phenomenon of figure 9 can be attributed to several factors. Firstly, the surface of A1 and A2 with relatively lower textures density was hardly able to store enough grease. When friction was carried out for a period of time, the lubricating grease stored in micro-textures was gradually consumed, resulting in the continuous increase of the friction coefficient. At the same time, it was very difficult to form a continuous lubricating film layer in the contact area lacking grease, which resulted in drastic fluctuation of the friction coefficient curve. Compared with A1 and A2, the friction coefficient of A3 with the average friction coefficient of 0.0799 was significantly decreased. More lubricating grease can be stored inside the dimples of surface with larger textures density, which was beneficial to generate hydrodynamic lubrication and form a continuous layer of lubricating film for 'secondary lubrication'. Yet it should be noted that it was difficult to provide lower friction coefficient if the textures density was extremely high. As shown in figure 9(a), the friction coefficient of A4 and A5 increased with increasing textures density. Although more grease can be stored, the pressure in the contact area of the friction pair increased due to the reduction of the actual contact area, which impeded grease from being supplied to the friction contact area in time and impaired the film-forming capability of lubricating film. Meanwhile, the relative action of the friction pair with insufficient lubrication led to an increase in the temperature of the contact area, which indirectly led to a decrease in the viscosity of the grease and a decrease in the lubricating effect of grease.

The friction coefficient of sample surface with different textures depth was shown in figure 10. Similar to figure 9, the friction coefficient of sample surface exhibited 'inverted-volcano-type' relationship with the increase of textures depth. The average friction coefficient of D3 with textures depth of 20 μm was the lowest, only 0.0799. The surface of sample with a depth shallower than or deeper than 20 μm presented higher friction coefficient, among which the curve of D1 with a depth of 4 μm possessed the highest friction coefficient with violent fluctuation. This was because textures depth of D1 was relatively shallow with less grease stored. With the friction test progressed, the lubricating grease was gradually squeezed out of the friction contact area, which resulted in insufficient lubrication of friction pair. At the same time, textures with shallow depth had poor ability to capture abrasive particles. The abrasive particles cannot be discharged in time, causing secondary abrasive wear, which led to serious fluctuation of friction curve. Compared with D1, the friction coefficient of D2 with a depth of 12 μm was decreased by 17%. Although the friction curve had no obvious fluctuation during the test, the curve of D2 showed an upward trend. This implied that the ability of textures to store lubricant and collect abrasive particles increased with the increase of textures depth, yet the limited textures depth was insufficient to fully improve the friction performance of sample surface. When the depth increased to 20 μm, compared with D1, the friction coefficient of D3 decreased significantly. Storing or releasing grease and forming hydrodynamic lubrication could be balanced by appropriate textures depth to provide the lowest friction coefficient, which was 27.8% lower than D2. With the further increase of textures depth, the friction coefficients of D4 and D5 increased in turn. It could be attributed to that in the process of laser surface texturing, there was stomata inside textures. As the depth of textures increased, the volume of stomata generated in textures increased synchronously, which decreased the space for storing grease in micro-textures. At the same time, due to the existence of stomata, negative pressure was formed in micro-textures during the test, resulting in extrusion-cavitation phenomenon [29]. This made it difficult for grease to be discharged from micro-textures, deteriorated the hydrodynamic lubrication in the friction contact area, and weakened the film-forming ability of the lubricating film, which further increased the friction coefficient of the sample surface.

Based on the above analysis, the friction coefficient of TC11 surface with textured coatings was significantly decreased as the wear resistance was effectively improved. At the same time, micro-textures with appropriate density and depth could further improve the friction coefficient of textured DLC coated surface, enhancing the tribological properties of titanium alloy.
5. Conclusion

Micro-textures with different density and depth was fabricated on the surface of titanium alloy with DLC coatings deposited. The synergistic anti-friction and anti-wear effects of textured coatings on titanium alloy sample under grease lubrication were studied and effects of density and depth of micro-textures on anti-friction effects of DLC coatings on titanium alloy surface were analyzed. The significant conclusions of this research are summarized as follows:

(1) The friction coefficient of textured DLC coated titanium alloy surface was as low as 0.0799, which was 80.6% lower than that of smooth titanium alloy.

(2) Compared with smooth titanium alloy surface, the surface of textured titanium alloy, coated titanium alloy and textured coated titanium alloy had only slight wear and scratches. Among the samples above, the wear volume of textured coated titanium alloy was decreased by 97.5%.

(3) Average friction coefficient of DLC coatings surface exhibited 'inverted-volcano-type' relationship with the increase of micro-textures density and depth. The sample with 30% textures density and 20 μm textures depth showed the optimal friction coefficient.

(4) Under grease lubrication conditions, synergistic anti-friction and wear-resistant system of laser surface micro-textures and surface DLC coatings could effectively improve the tribological properties of titanium alloy, which showed favorable application prospects in the field of high-end lightweight parts under special conditions such as aerospace and rail transit.

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References

[1] Peters M et al 2003 Titanium alloys for aerospace applications Adv. Eng. Mater. 6 419–27
[2] Balazic M et al 2007 Review: titanium and titanium alloy applications in medicine Int. J. Nano and Biomaterials 1 3–34
[3] Gurrappa I 2003 Characterization of titanium alloy Ti-6Al-4V for chemical, marine and industrial application Mater. Charact. 51 131
[4] Farhad N 2001 Machining of aerospace titanium alloys Robot. Comp-Int. Manuf. 17 99–106
[5] Maehara K et al 2002 Application of vanadium-free titanium alloys to artificial hip joints Mater. Trans. 43 2936–42
[6] Peacock D K, Eng C and Corr F I M I 2000 Effective design of high performance corrosion resistant systems for oceanic environments using titanium Corros. Rev. 18 295–300
[7] Wang Y M et al 2006 Tribological behavior of microarc oxidation coatings formed on titanium alloys against steel in dry and solid lubrication sliding Appl. Surf. Sci. 252 2989–98
[8] Lin N M et al 2018 Surface texture-based surface treatments on Ti6Al4V titanium alloys for tribological and biological applications: a mini review (Review) Materials 11 1996–1944
[9] Kachoei M et al 2016 Zinc-oxide nano-coating for improvement of the antibacterial and frictional behavior of nickel-titanium alloy Nanomedicine 11 1748–6963
[10] Amanov A et al 2013 Improvement in the tribological characteristics of Si-DLC coating by laser surface texturing under oil-lubricated point contacts at various temperatures Surf. Coat. Tech. 232 549–60
[11] Coblas D G et al 2015 Manufacturing textured surfaces State of art and recent developments P. I. Mech. Eng. J-J. Eng. 229 3–29
[12] Allahyari E et al 2019 Laser surface texturing of copper and variation of the wetting response with the laser pulse fluence Appl. Surf. Sci. 470 817–24
[13] Romano J-M et al 2019 Mechanical durability of hydrophobic surfaces fabricated by injection moulding of laser-induced textures Appl. Surf. Sci. 476 850–60
[14] Segu D Z and Wang P H 2015 Friction control by multi-shape textured surface under pin-on-disc test Tribol. Int. 91 111–7
[15] Hua X J et al 2017 Experimental analysis of friction and wear of laser microtextured surface filled with composite solid lubricantand lubricated with grease on sliding surfaces J. Tribol. 139 021609
[16] Hua X J et al 2020 Tribological behavior and abrasion resistant mechanism of Laser/Micro-Bulge texturing surface under full oil lubrication Tribol. T (https://doi.org/10.1080/10402004.2020.1738610)
[17] Grabon W et al 2013 Improving tribological behaviour of piston ring–cylinder liner frictional pair by liner surface texturing Tribol. Int. 61 102–8
[18] Wu Z et al 2017 Tribological properties of dimple-textured titanium alloys under dry sliding contact Surf. Coat. Tech. 309 21–8
[19] Al Mahmud K A H et al 2015 An updated overview of diamond-like carbon coating in tribology Crit. Rev. Solid State. 40 90–118
[20] Kovaci H et al 2018 Tribological behavior of DLC films and duplex ceramic coatings under different sliding conditions Ceram. Int. 44 7151–8
[21] Wang S et al 2014 Different tribological behaviors of titanium alloys modified by thermal oxidation and spraying diamond like carbon Surf. Coat. Tech. 252 0257–8972
[22] Cicek H et al 2018 Adhesion and multipass scratch characterization of TiC:Ta-DLC composite coatings Diam. Relat. Mater. 83 80–6
[23] Bhattacharjee S et al 2015 Enhancement of adhesion and corrosion resistance of diamond-like carbon thin films on Ti–6Al–4V alloy by nitrogen doping and incorporation of nanodiamond particles Surf. and Coat. Tech. 284 153–8
[24] Hua X J et al 2016 Research on discriminating partition laser surface micro-texturing technology of engine cylinder Tribol. Int. 98 190–6
[25] Mosayebi M J and Hosseini S R 2015 Structural and tribological properties of TiC–DLC coatings deposited by RCAE-PVD at various bias voltages Surf. Eng. 31 96–102
[26] Zhou J et al 2016 Experimental study on laser microstructures using long pulse Opt. Laser Eng. 78 113–20
[27] Wu J-H et al 2005 Tribological characteristics of diamond-like carbon (DLC)-based nanocomposite coatings Wear 259 744–51
[28] Huang L et al 2019 Effect of TiC particles on three-body abrasive wear behaviour of low alloy abrasion-resistant steel Wear 434 202971
[29] Gropper D, Wang L and Harvey T J 2016 Hydrodynamic lubrication of textured surfaces: a review of modeling techniques and key findings Tribol. Int. 94 509–29