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Experimental investigation of tribological properties of laser textured Tungsten doped Diamond like Carbon coating under dry sliding conditions at various loads.

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Abstract:

Laser micro texturing technique has shown its potential in reducing friction and wear at various mechanical interfaces such as automotive and cutting tools etc.. Automotive parts are coated with Diamond-like Carbon (DLC) coatings to enhance their performance. Due to stringent condition at the automotive contacts and demand for performance enhancement, increase in performance of DLC coatings is required. In this study laser micro texturing is being combined with tungsten doped DLC coating. In order to analyze the benefits of laser micro texturing on tungsten doped DLC coating. Tribological testing was conducted on a reciprocating test rig at various loading conditions. The results indicated that laser textured tungsten doped DLC coating showed the lower coefficient of friction compared to un-textured tungsten doped DLC coating at a load of 15 N, 25 N and 35 N. Higher graphitization was observed in the case of un-textured coating at 35 N load.

Keywords:

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Laser surface texturing, Tungsten doped DLC, Friction, Wear, Dry sliding

1. Introduction:

Reduction in friction to enhance automotive fuel efficiency is an important research topic for several decades. Several techniques have been devised over the years such as surface modifications and lubricant oil modifications. Laser micro texturing is a relatively new technique for reducing friction at automotive components. Surface modification in the form of asperities was introduced in 1966 by Hamilton et al. [1, 2]. They found that a seals load carrying ability can be improved with micro asperities[1, 2]. Since then several analytical and experimental studies have been conducted to analyze tribological effects due to change in shape of textures, size of textures, sliding direction, placement angle, etc.. Surface modification has been useful for reducing friction and wear at various mechanical interfaces. Various types of textures have been created such as micro dimples[3] and micro grooves[4].

Various applications of micro surface texturing are automotive[2, 5-15], cutting tool[16-20], mechanical seals[21, 22], sports equipment [23] and biomedical applications [24, 25]. The basic mechanisms of micro texturing are as follows: they behave as a micro hydrodynamic bearing, they act as wear debris traps, they supply lubricant at the contact [26]. Micro textures can be created by lasers[27], Vibro-mechanical texturing[28], Micro EDM[29], chemical etching[30], micro grinding[31] etc..

Various coatings have been used in automotive engines to lower wear/tear and reduce friction; thus increasing the life of a component and reduce fuel consumption. Among them are carbide coatings such as CrN, Ti-TiN, ZrN, CrAlNi [32] and Diamond-like Carbon coatings such as a-C:H, ta-C, and a-C:H:W. DLC coatings are famous because they possess excellent tribological and mechanical properties in rolling sliding contacts [33] [34]. Various components in IC engines such as piston rings, bearings, valves, and tappets are coated with DLC [35]. Applications of DLC coatings include automotive[35-37], cutting tools[38, 39] and medical applications[40].

To further enhance the service life of components, researchers have doped DLC coatings with Hydrogen, various metals, carbides and nitrides [41]. W-DLC is one such coating in which DLC coating is doped with tungsten. W-DLC coatings show high hardness, adhesion to the substrate, low friction and wear[42]. Tribological properties have been evaluated for gears by Joachim et al. [43]. They showed that W-DLC coated gears have higher macro pitting and load-carrying capacity[44].

A combination of laser micro texturing and DLC coatings has recently been found to provide higher wear resistance than un-textured DLC coatings [8, 9, 45, 46]. Researchers have combined amorphous hydrogenated carbon coating (a-C:H) [45], amorphous carbon (a-C) [47], Silicon doped Diamond-like Carbon coating (Si-DLC) [46] and tetrahedral amorphous carbon (ta-C) [8] with laser texturing. To date, the effects of laser texturing on W-DLC coatings have not been studied. W-DLC is being used to coat automotive components, it is important to analyze whether micro texturing plays a positive role in the overall performance enhancement or not. The purpose of this article is to analyze whether micro texturing is beneficial in enhancing the tribological properties of W-DLC coatings or not. Dry sliding was conducted so that the positive or negative effects of micro-textures can be observed without the addition of complex mechanisms of automotive lubricant or the additives that are present in them.

2. Methodology:

2.1 Sample Preparation:

The configuration used for Tribological testing was a ball on flat. The ball was made of AISI52100 steel and the plate was coated with W-DLC. The ball material was selected as it is used to make automotive parts. The properties are mentioned in Table 1. The substrate was made of hardened steel, the substrate was cut from a bulk material according to test rig specimen size (thickness, length, and width of 4-5 mm, 15 mm and 15 mm, respectively). After cutting, the samples were hardened to achieve a hardness of 58-62 HRC. For the ease of cutting, samples were hardened after cutting. To reduce the surface roughness of substrate various grit size sandpapers (100 to 3000) were used. After using sandpapers, polishing was conducted using a diamond suspension (size- 6 µm to 1 µm). After polishing, laser micro surface texturing was conducted. Dimples were created using Picosecond laser. Laser power, pulse duration, beam position speed and wavelength were 10 W, 10.3 ps, 1000 mm/s and 1640 nm, respectively. Ultrafast lasers such as (picoseconds and femtosecond) are mostly used for micro texturing[48]. They can be used to make well controlled micro and nano textures [48]. The lower cost of pico-second lasers make them suitable for several commercial application[49]. The scope of this paper is limited to wear behavior of textured coatings rather than effects of laser on material properties. The depth and diameter of micro-texture were around 6-8 µm and ~ 50 µm, respectively. These texture parameters have been found previously to enhance tribological properties[9]. After the micro texturing, the bulges were removed by light polishing with diamond suspension (0.5 µm). According to Amanov et al.[46], bulges are formed around the dimples, additionally, areas nearby to dimples experience melting, thermal and rapid re-solidification. After laser texturing W-DLC was deposited. The deposition was conducted by Oerlikon Balzers Ltd. The properties can be found in the paper [50].

2.2 Tribological testing and wear track characterization:

Tribological testing was conducted on a reciprocating test rig at loads, frequency and temperature of 15, 25 and 35 N, 10 Hz and 28-30 ◦C, respectively. Reciprocating test rig (DUCOM TR 282) was used for tribo testing. The duration of test was 1 hr. Each test was repeated three times to ensure repeatability. The wear of counter surface balls was measured using an optical microscope. After tribological testing, the samples were cleaned with n-heptane and placed in desiccators for further investigation. To analyze the surface morphology and elemental composition, scanning electron microscope (SEM) (Hitachi Model No. TM3030) and Energy dispersive spectroscopy (Hysitron, Inc., Model No. TI750 UBI™) was used.

3.1 Results and Discussion:

Figure 1 shows that in the start, the increase in friction is abrupt, however after 500 seconds; the increase in friction became smoother. This can be related to unsteady friction behavior in the running-in period. Similar behavior has been observed by Kummel et al. [51]. As this test has been conducted without lubricants, the steady-state average friction coefficient is higher.

At a load of 15 N, in the case of W-15t (textured coated sample at 15 N load) sample, the average friction coefficient is 0.147 compared to W-15 (coated sample at 15 N load) sample which showed average friction coefficient of 0.165. This shows that in dry sliding condition, micro-textures can help in the reduction of friction coefficient. Previously, reduction of COF had been observed in the case of lubricated sliding condition for DLC coated samples [46, 47].

At a load of 25 N, in the case of the W-25t sample, the COF value is 0.1495. Whereas in the case of the W-25 sample, the COF value is 0.1665. At a load of 35 N, in the case of the W-

35t sample, the COF value is 0.149. Whereas in the case of the W-35 sample; the COF is 0.166. The COF results at 25 and 35 N load shows that micro-textured samples show lower COF compared to un-textured cases in dry sliding conditions. Another indication that can be obtained from Figures 1a, 1b, 1c is that in the case of textured samples, friction trend after 2500 s is smoother compared to un-textured cases. This behavior can be attributed to the capture of wear debris by micro-textures, which reduced the friction instability[45]. This has been observed by He et al. in the case of H-DLC coating[45]. Takeno et al. [52] observed that due to the rolling effect of tungsten oxide debris the friction coefficient is unstable. They proposed the mechanism that due to the reaction of tungsten and oxygen, tungsten oxide debris is formed. The debris comes in and out of the sliding track, which causes unstable friction [52]. Mustafov et al. [35] also observed instable friction of W-DLC in the case of dry tests of untextured samples. The authors deduced that the formation of the transfer layer is responsible for friction variation in dry sliding conditions [35]. Figure 2 shows the average COF of various samples. It can be seen that textured samples showed lower average COF than un-textured samples.

3.2 Wear track characterization:

The wear scar diameter of the counter surface ball is shown in Figure 3. The trend is similar to the trend of COF. At a load of 15 N, W-15t counter ball showed wear scar diameter of 321.7 µm. Whereas W-15 counter ball showed wear scar of 618.7 µm. At a load of 25 N, the counter ball which rubbed against W-25t and W-25 showed wear scar diameters of 360.53 µm and 594.3 µm, respectively. At a load of 35 N, the counter ball which rubbed against W-35t and W35 showed wear scar diameter of 403.9 and 703.9 µm. The results show that with the increase in load, counter ball wear also increases. Additionally, the counter ball which rubbed against textured W-DLC samples showed lower wear scar compared to un-textured W-DLC samples. Figure 4 shows optical microscope images of wear scar of counter balls.

Figure 5 shows the SEM images of various micro-textured and un-textured W-DLC coated samples at various loads. The W- DLC generally showed a nodular structure as observed by other authors [50, 53]. Figure 5 (h) shows the W-DLC before testing. Table 2 shows the EDX of samples. The SEM result of W-15 shows small localized scratches; additionally, the nodules on the surface were also removed. The surface of W-15t shows wear induced smoothening (polishing wear). The wear induced smoothening has also been observed by Ronkainen et al. [53]. At the wear track of W-15t, the dimples were full of coating material; one example is shown in Figure 5 b. This is one of the reasons that abrasive wear marks were not observed on the surface of W-15t, as they were trapped by the dimples. He et al. [45] in the case of textured H-DLC observed similar behavior, where micro dimples stored the wear debris to reduce wear.

Sample W-25 shows a thick layer of coating materials on the surface of wear track at some points, as shown in the figure. 5 c. In the case of W-25t (figure 5 d), the coating material can be seen to be trapped by the dimple. The wear track of W-35 (figure 5 e and f) shows a thick coating material layer at some points and wear induced smoothening at other points. SEM image of W-35t (figure 5g) showed that dimple trapped wear debris. SEM images of all the samples show that the delamination of coating didn’t occur in the case of textured or un-textured W-DLC coating. This indicates that coating adhesion to the substrate was excellent.

Table 3 shows the EDX results of tested samples. At a load of 15 N, W-15 and W-15t shows a reduction of C content and increase in W and O content compared to as-deposited sample. At a load of 25 N, W-25 showed higher O content compared to the W-25t, this can be due to the presence of oxide rich films at the wear track. At a load of 35 N, sample W-35 showed higher O content similar to the W-25 sample compared to W-35t. Takeno et al. [52] suggested the formation of tungsten oxide debris. Formation of beneficial tribolayer has also been suggested by Ronkainen et al. [54].

Raman spectroscopy was conducted to analyze the structural changes of W-DLC coating before and after testing. The graphitization of W-DLC coating has been observed by other authors [50]. Before wear testing, the Id/Ig ratio was 1.49. After wear testing, W-35 and W-35t showed the Id/Ig ratio of 4.39 and 2.92. W-35 showed higher Id/Ig compared to W-35t. The results indicate that higher graphitic transformation in the case of un-textured W-DLC compared to textured W-DLC at 35 N load. Graphitization can be induced due to micro-wear debris present at the wear track. Due to these wear particles, the load per unit area increases at the contact point, which lowers the temperature at which graphitization occurs [47]. In the case of the textured sample, figure 5g shows that the dimple is full of wear debris. The lower wear induced graphitization in the case of textured samples can be due to wear debris entrapment by the dimples. The results indicate that the depth of dimples maybe increased in the case of dry sliding conditions, as 6-8 μm may be not enough to entrap all the wear debris during operation. This may further reduce the wear induced graphitization in the case of textured samples.

4. Conclusions:

The effect of laser texturing was investigated on tungsten doped DLC coating under dry sliding conditions under various contact loads.

1. At a load of 15 N, sample W-15t showed lower COF compared to sample W-15. This can be attributed to the entrapment of micro-wear particles by the micro-textures.

2. At a load of 25 N, COF increased in the case of both W-25t and W-25 compared to W-15t and W-15. However, even at higher load W-25t showed lower wear compared to W-25.
3. COF increase didn't occur at a load of 35 N compared to 25 N. This can be because of graphitization phenomena. Even at high load, micro-textured W-DLC showed lower COF than un-textured W-DLC.
4. Counter ball wear scar reduced in the case of micro-textured W-DLC coating compared to counter balls which rubbed against un-textured samples.
5. Laser micro texturing can be used to enhance the tribological performance of W-DLC coated automotive parts.

List of Figures

Figure No. 1. Coefficient of friction of textured and un-textured W-DLC coating at various loads (a) 15 N (b) 25 N (c) 35 N

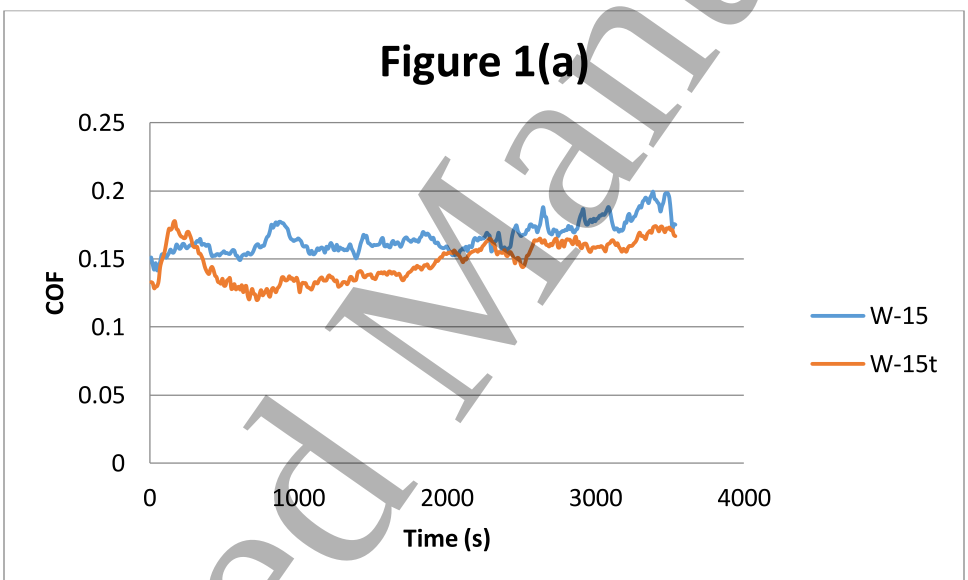
Figure No. 2. Average COF of textured and un-textured W-DLC coating at various loads

Figure No. 3. Wear scar diameter of the counter surface at various loads.

Figure No. 4. Optical microscope images of Ball wear scar at various loads. (a)W-15(b) W-15t (c)W-25 (d) W-25t (e)W-35 (f) W-35t

Figure No. 5 Scanning electron Microscope images of wear track of textured and un-textured W-DLC at various loads. (a)W-15 (b) W-15t (c)W-25 (d) W-25t (e)W-35 (f) W-35 (g) W-35t (h) as-deposited

List of Tables



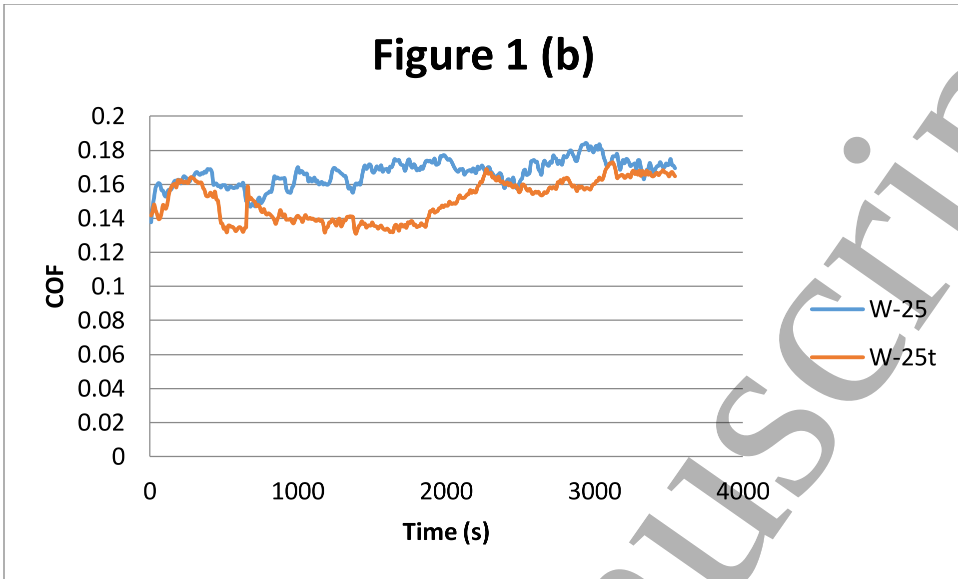


Figure 1 (b)
COF
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
1000
2000
3000
4000
Time (s)
W-25
W-25t

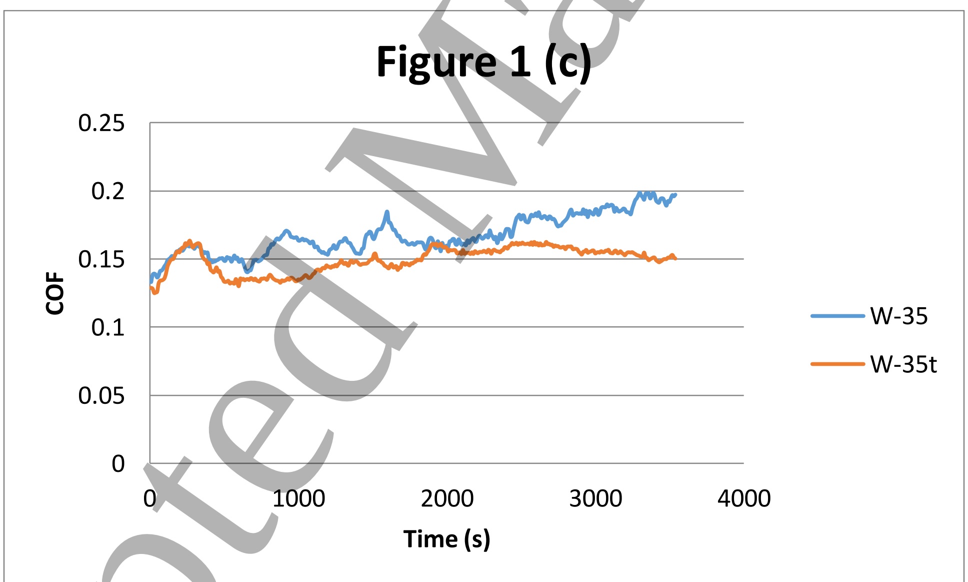
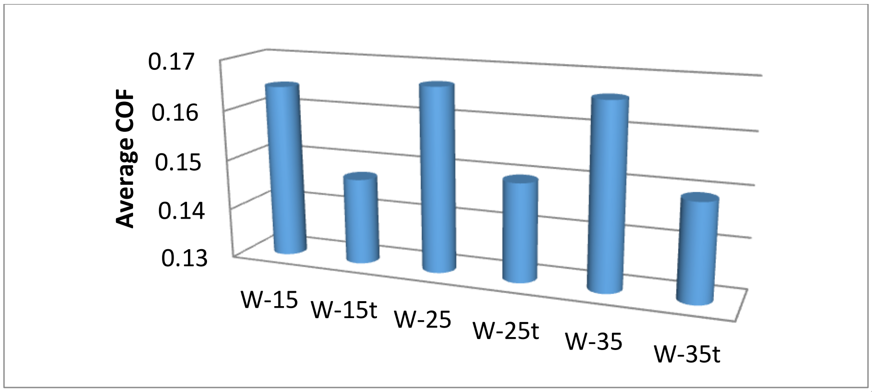


Figure 1 (c)
COF
0.25
0.2
0.15
0.1
0.05
0
0
1000
2000
3000
4000
Time (s)
W-35
W-35t

Figure No. 1.



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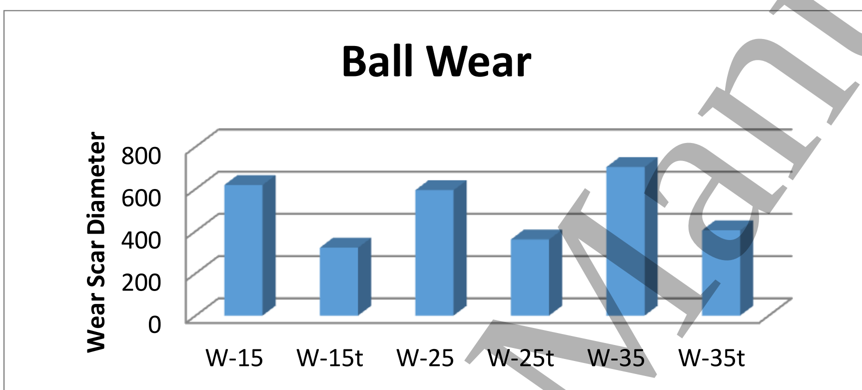

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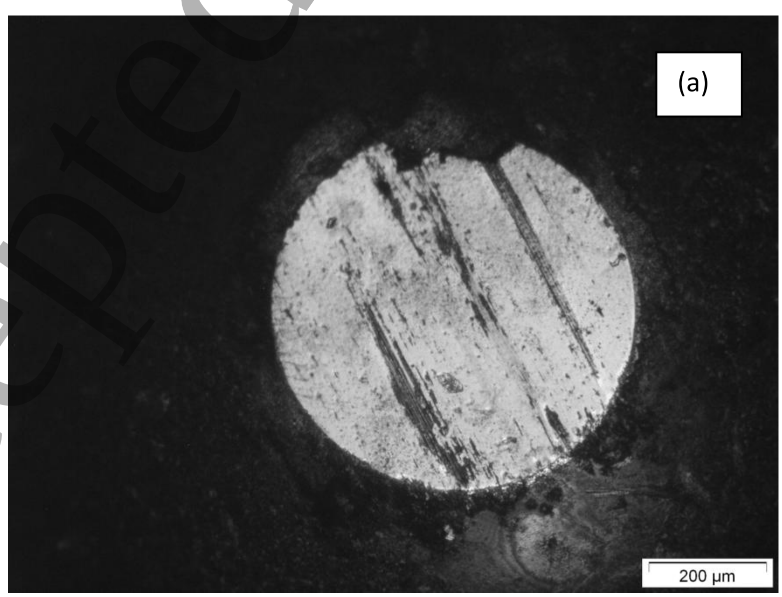

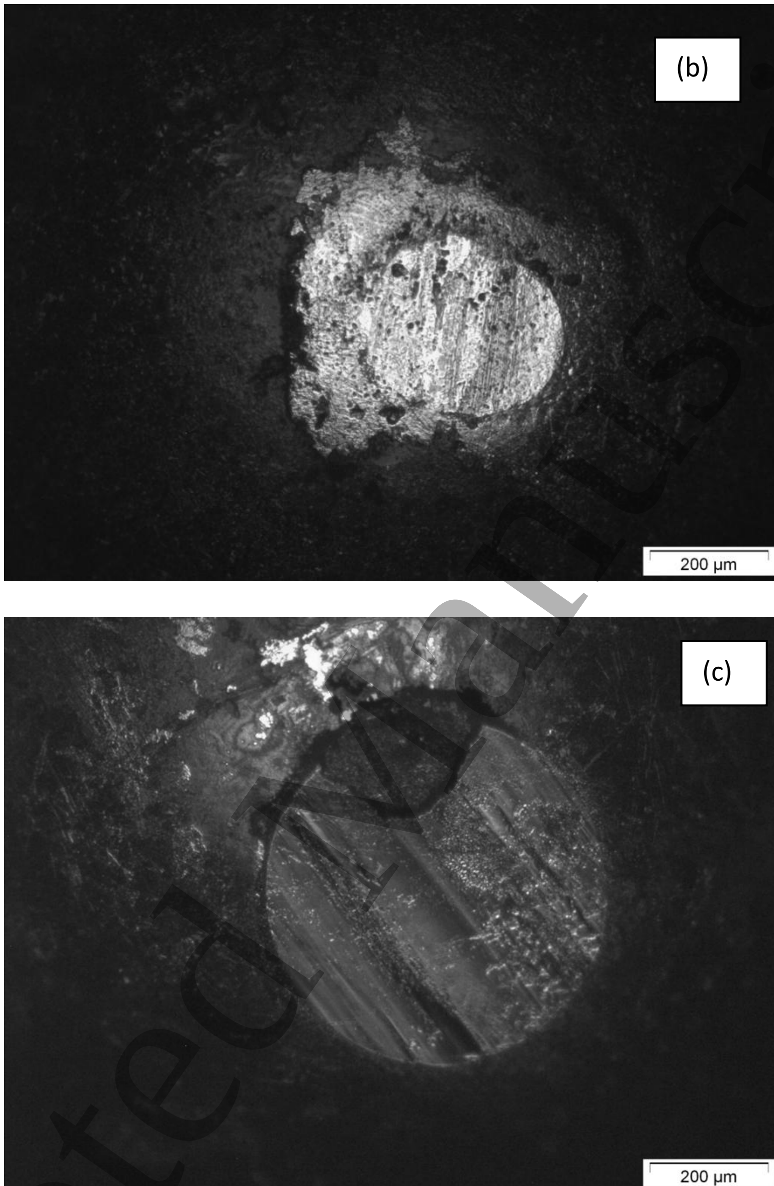
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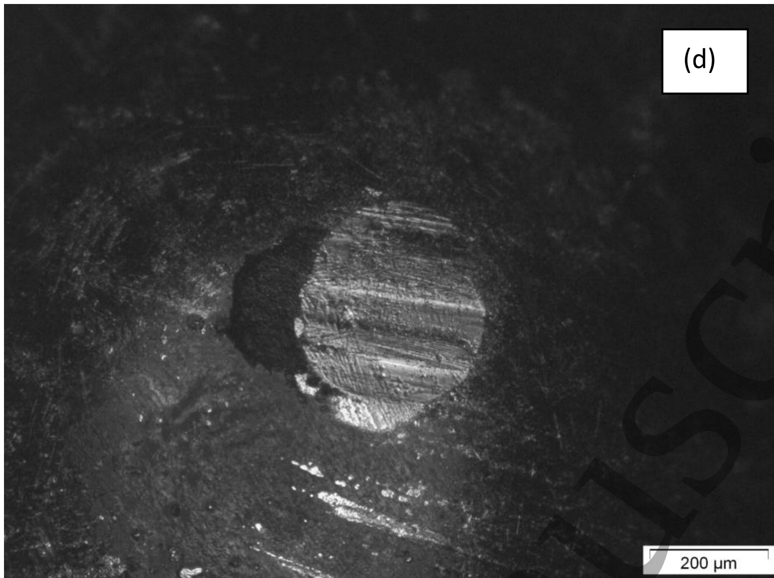
(c)
200 µm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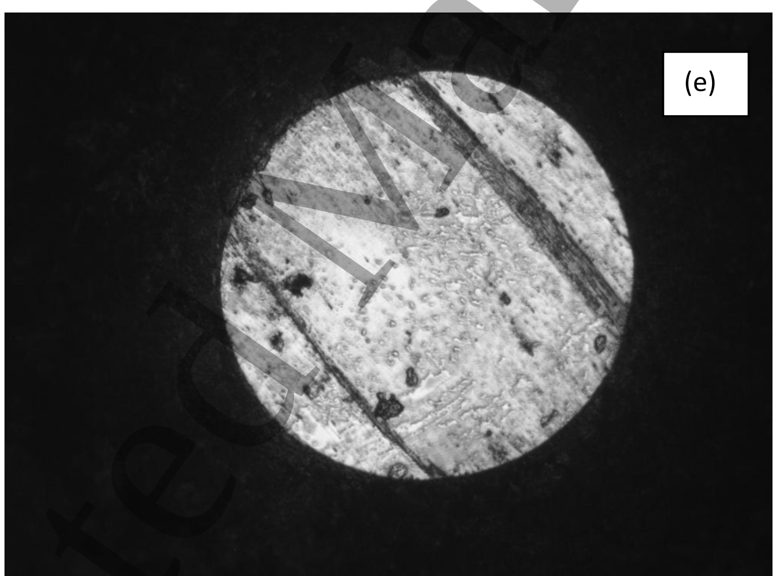
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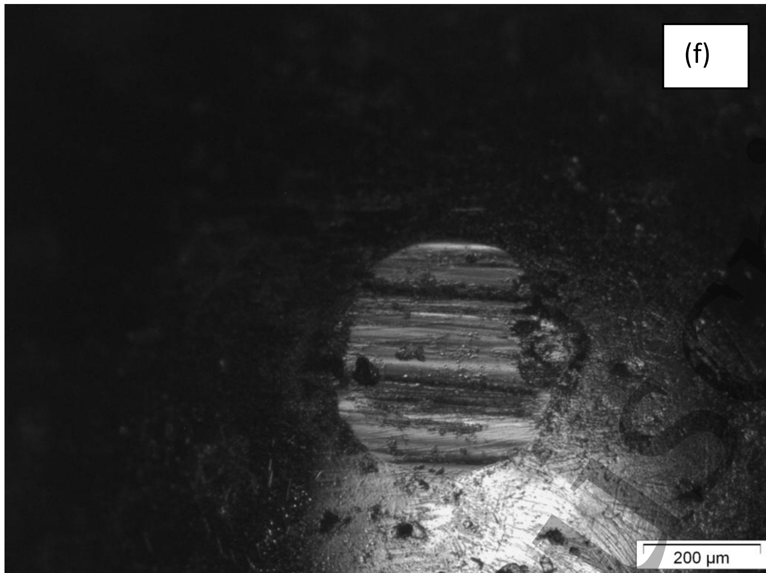

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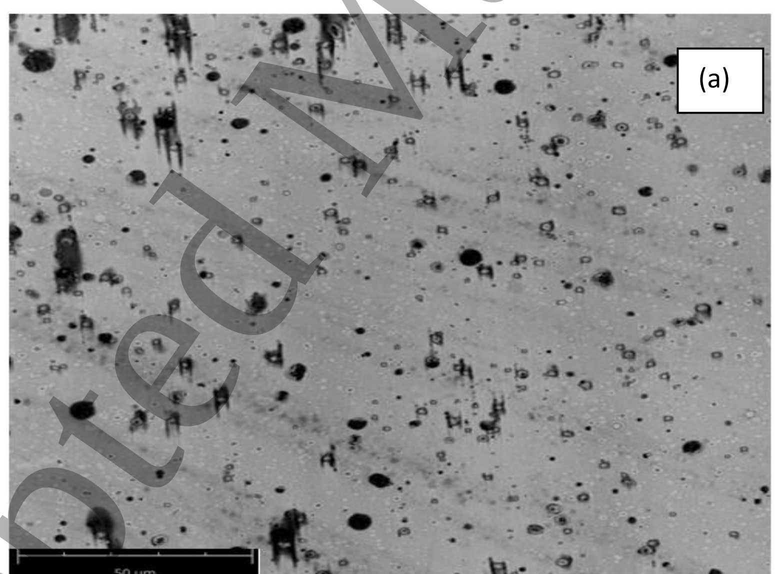

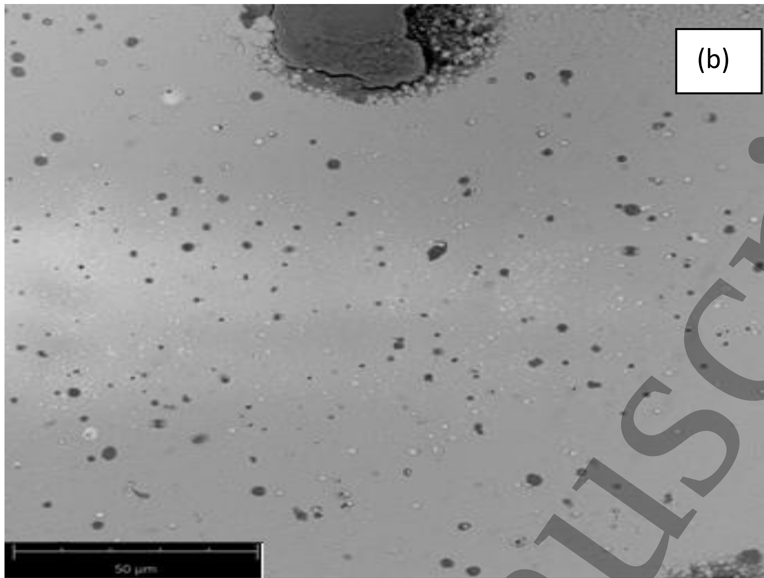
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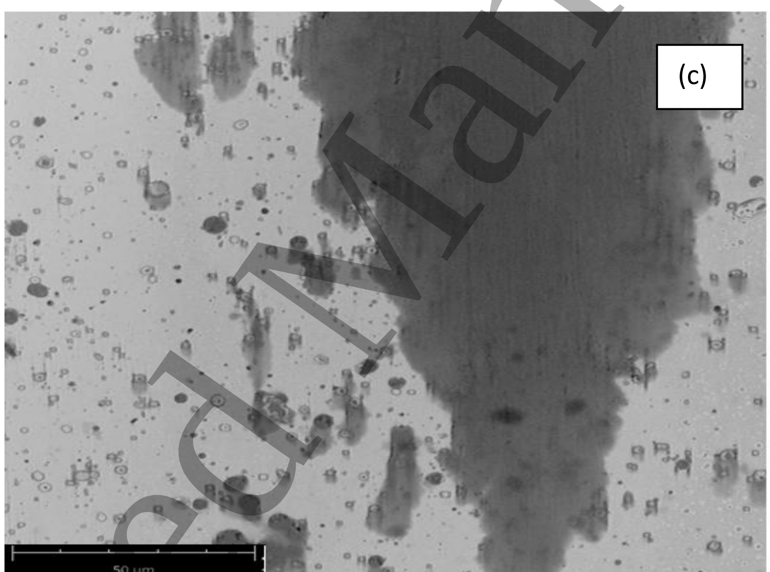
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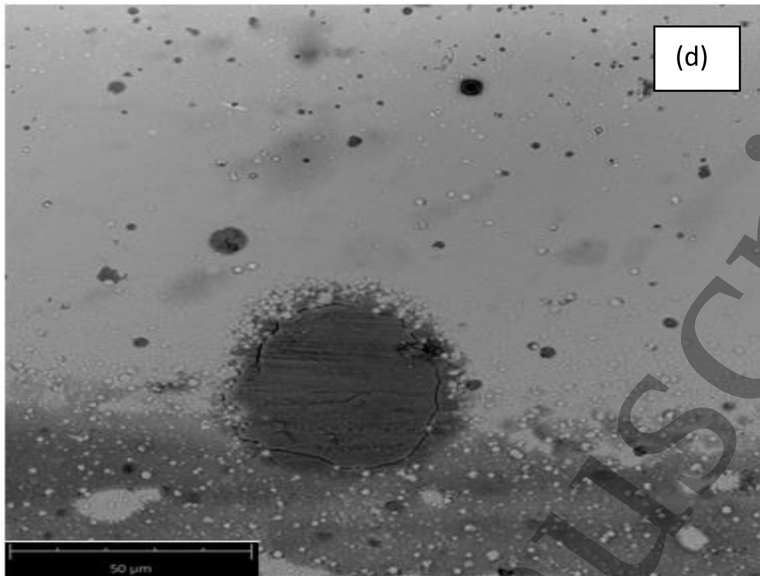
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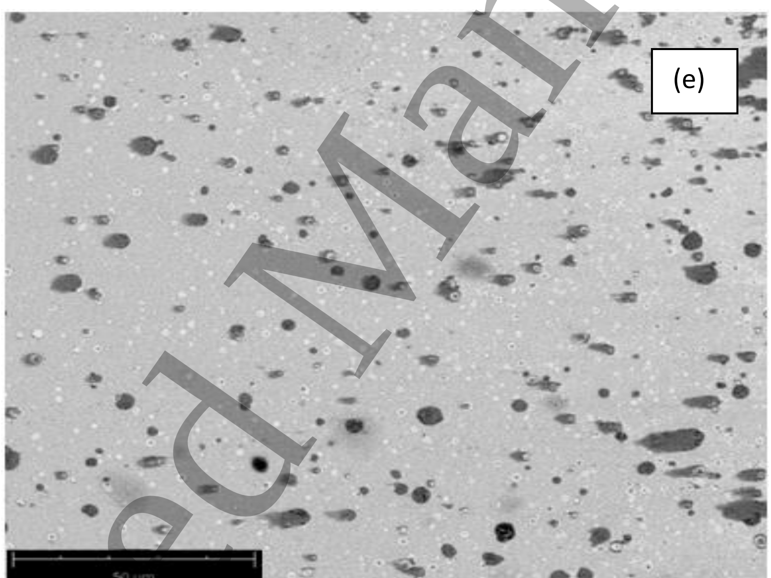
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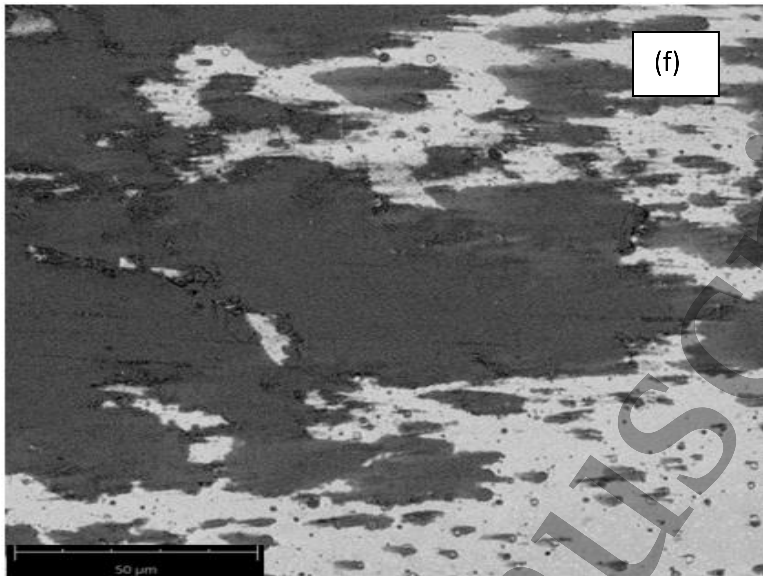
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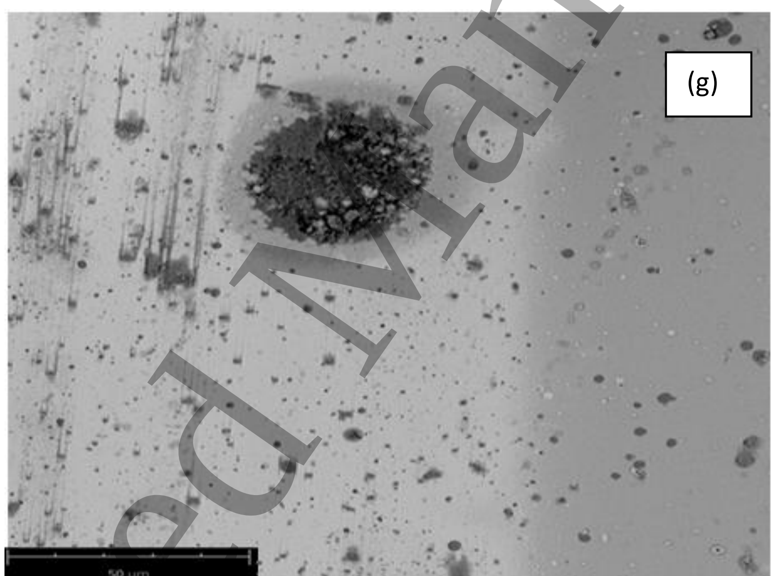
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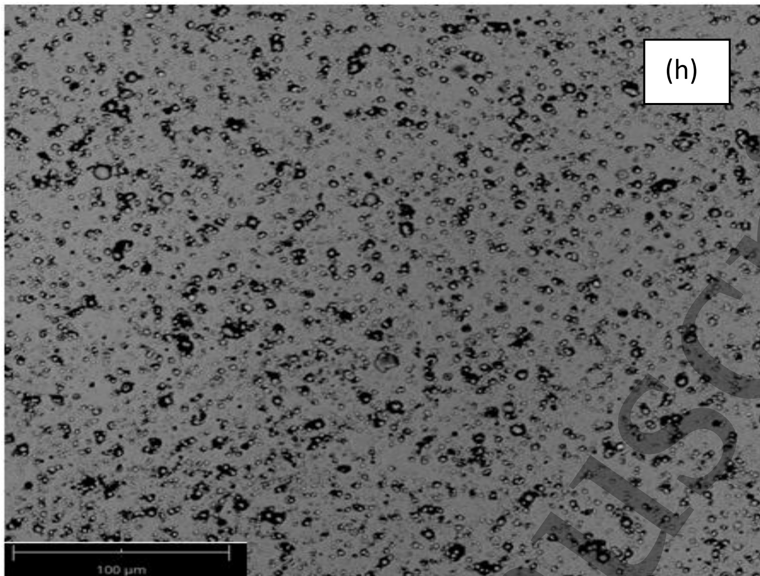

Figure No. 5.

Table No. 1

Physical Properties	**Steel Ball**	**DLC coating**
Material	AISI-52100	W-DLC
Hardness	~62 HRC	12–15 GPa
Composition	Fe 96.5 %, C 0.98 %, Mn 0.250 %, Si 0.150%, Cr 1.30%, P ≤ 0.0250, S ≤ 0.0250	Hydrogen 15 % (atomic weight)
Roughness (average)	40 nm	-

Thickness	-	2-3 µm
Interlayer	-	CrN

Table No. 2

Sample	Carbon	Tungsten	Oxygen	Nickle	Chromium	Iron
W	74.56	18.53	3.9	-	1.4	1.61
W-15	53.95	32.43	8.18	2.40	1.84	1.20
W-15t	49.95	36.34	9.15	2.42	1.32	0.82
W-25	20.83	24.02	43.6	2.19	2.64	6.72
W-25t	38.74	32.70	21.05	4.15	-	3.36
W-35	14.93	18.20	50.07	1.02	2.71	13.07
W-35t	33.45	43.63	12.84	2.63	5.46	1.99

Table No. 3

Sample Name	Id/Ig ratio
W-DLC (Before Test)	1.49
W-DLC (After Test)	4.39
W-DLC Textured (After Test)	2.92

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References:

1. Hamilton, D., J. Walowit, and C. Allen, *A theory of lubrication by microirregularities.* Journal of Basic Engineering, 1966. **88**(1): p. 177-185.
2. Rao, X., et al., *Effects of thread groove width in cylinder liner surface on performances of diesel engine.* Wear, 2019. **426-427**: p. 1296-1303.
3. Liu, X., W. Zhang, and G. Sun, *The influence of textured interface on DLC films prepared by vacuum arc.* Surface and Coatings Technology, 2019. **365**: p. 143-151.
4. Boidi, G., et al., *Effect of laser surface texturing on friction behaviour in elastohydrodynamically lubricated point contacts under different sliding-rolling conditions.* Tribology International, 2019.
5. Zavos, A. and P.G. Nikolakopoulos, *Cavitation effects on textured compression rings in mixed lubrication.* Lubrication Science, 2016. **28**(8): p. 475-504.
6. Vlădescu, S.-C., et al., *Combined friction and wear reduction in a reciprocating contact through laser surface texturing.* Wear, 2016. **358-359**: p. 51-61.
7. Vlădescu, S.-C., et al., *Lubricant film thickness and friction force measurements in a laser surface textured reciprocating line contact simulating the piston ring–liner pairing.* Tribology International, 2016. **98**: p. 317-329.
8. Arslan, A., et al., *Wear characteristics of patterned and un-patterned tetrahedral amorphous carbon film in the presence of synthetic and bio based lubricants.* Materials Research Express, 2018. **6**(3): p. 036414.
9. Arslan, A., et al., *Investigation of laser texture density and diameter on the tribological behavior of hydrogenated DLC coating with line contact configuration.* Surface and Coatings Technology, 2017. **322**: p. 31-37.
10. Shen, C. and M.M. Khonsari, *The effect of laser machined pockets on the lubrication of piston ring prototypes.* Tribology International, 2016. **101**: p. 273-283.
11. Profito, F.J., et al., *Transient experimental and modelling studies of laser-textured micro-grooved surfaces with a focus on piston-ring cylinder liner contacts.* Tribology International, 2016.
12. Hua, X., et al., *Research on discriminating partition laser surface micro-texturing technology of engine cylinder.* Tribology International, 2016. **98**: p. 190-196.
13. Gu, C., et al., *Effects of surface texturing on ring/liner friction under starved lubrication.* Tribology International, 2016. **94**: p. 591-605.
14. Zavos, A.B. and P.G. Nikolakopoulos, *Simulation of piston ring tribology with surface texturing for internal combustion engines.* Lubrication Science, 2015. **27**(3): p. 151-176.
15. Chen, Y., et al., *Multi-objective optimization of micron-scale surface textures for the cylinder/valve plate interface in axial piston pumps.* Tribology International, 2019. **138**: p. 316-329.
16. Arslan, A., et al., *Surface Texture Manufacturing Techniques and Tribological Effect of Surface Texturing on Cutting Tool Performance: A Review.* Critical Reviews in Solid State and Materials Sciences, 2016: p. 1-35.

17. Pal, V.K. and S.K. Choudhury, *Fabrication of texturing tool to produce array of square holes for EDM by abrasive water jet machining.* The International Journal of Advanced Manufacturing Technology, 2015.
18. Qu, N.S., et al., *Modified microscale pattern transfer without photolithography of substrates.* Journal of Materials Processing Technology, 2015. **218**: p. 71-79.
19. Zhang, K., et al., *Effect of microscale texture on cutting performance of WC/Co-based TiAlN coated tools under different lubrication conditions.* Applied Surface Science, 2015. **326**: p. 107-118.
20. Kim, D.M., et al., *Influence of a micropatterned insert on characteristics of the tool–workpiece interface in a hard turning process.* Journal of Materials Processing Technology, 2016. **229**: p. 160-171.
21. Ahmed, A., et al., *An overview of geometrical parameters of surface texturing for piston/cylinder assembly and mechanical seals.* Meccanica, 2015: p. 1-15.
22. Adjemout, M., N. Brunetière, and J. Bouyer, *Friction and Temperature Reduction in a Mechanical Face Seal by a Surface Texturing: Comparison between TEHD Simulations and Experiments.* Tribology Transactions, 2018. **61**(6): p. 1084-1093.
23. Yu, S.S., et al., *Textured hybrid nanocomposite coatings for surface wear protection of sports equipment.* Surface and Coatings Technology, 2016. **287**: p. 76-81.
24. Ghosh, S. and S. Abanteriba, *Status of surface modification techniques for artificial hip implants.* Sci Technol Adv Mater, 2016. **17**(1): p. 715-735.
25. Cunha, A., et al., *Femtosecond laser surface texturing of titanium as a method to reduce the adhesion of Staphylococcus aureus and biofilm formation.* Applied Surface Science, 2016. **360**: p. 485-493.
26. Shimizu, J., et al., *Friction characteristics of mechanically microtextured metal surface in dry sliding.* Tribology International, 2019.
27. Zhang, X., et al., *Laser textured Ti-6Al-4V surfaces and grinding performance evaluation using CBN grinding wheels.* Optics & Laser Technology, 2019. **109**: p. 389-400.
28. Greco, A., et al., *Surface Texturing of Tribological Interfaces Using the Vibromechanical Texturing Method.* Journal of Manufacturing Science and Engineering, 2009. **131**(6): p. 061005.
29. Koshy, P. and J. Tovey, *Performance of electrical discharge textured cutting tools.* CIRP Annals - Manufacturing Technology, 2011. **60**(1): p. 153-156.
30. Coblas, D.G., et al., *Manufacturing textured surfaces: State of art and recent developments.* Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 2014. **229**(1): p. 3-29.
31. Xie, J., et al., *Micro-grinding of micro-groove array on tool rake surface for dry cutting of titanium alloy.* International Journal of Precision Engineering and Manufacturing, 2012. **13**(10): p. 1845-1852.
32. Mehran, Q.M., et al., *A Critical Review on Physical Vapor Deposition Coatings Applied on Different Engine Components.* Critical Reviews in Solid State and Materials Sciences, 2017. **43**(2): p. 158-175.
33. Donnet, C. and A. Erdemir, *Tribology of diamond-like carbon films: fundamentals and applications*. 2007: Springer Science & Business Media.
34. Yao, N., A.G. Evans, and C.V. Cooper, *Wear mechanism operating in W-DLC coatings in contact with machined steel surfaces.* Surface and Coatings Technology, 2004. **179**(2-3): p. 306-313.
35. Mutafov, P., et al., *DLC-W coatings tested in combustion engine — Frictional and wear analysis.* Surface and Coatings Technology, 2014. **260**: p. 284-289.
36. Koszela, W., et al., *The combined effect of surface texturing and DLC coating on the functional properties of internal combustion engines.* Tribology International, 2018. **127**: p. 470-477.

37. Gangopadhyay, A., et al., *Valvetrain Friction Reduction through Thin Film Coatings and Polishing.* Tribology Transactions, 2012. **55**(1): p. 99-108.
38. Brzezinka, T.L., et al., *DLC and DLC-WS2 Coatings for Machining of Aluminium Alloys.* Coatings, 2019. **9**(3): p. 192.
39. Badiger, P.V., V. Desai, and M.R. Ramesh, *Performance of DLC coated tool during machining of MDN431 alloyed steel.* Materials Today: Proceedings, 2018. **5**(9, Part 1): p. 17360-17370.
40. Timan Idriss Gasab, M., et al., *Advanced DLC coating technique on silicone-based tubular medical devices.* Surface and Coatings Technology, 2016. **307**: p. 1084-1087.
41. Neville, A., et al., *Compatibility between tribological surfaces and lubricant additives—How friction and wear reduction can be controlled by surface/lube synergies.* Tribology International, 2007. **40**(10-12): p. 1680-1695.
42. Yue, W., et al., *Effects of Tungsten Doping Contents on Tribological Behaviors of Tungsten-Doped Diamond-Like Carbon Coatings Lubricated by MoDTC.* Tribology Letters, 2015. **58**(2).
43. Joachim, F., N. Kurz, and B. Glatthaar, *Influence of coatings and surface improvements on the lifetime of gears.* Gear Technology, 2004. **21**(4): p. 50-56.
44. Tamura, Y., et al., *Interaction of DLC and B4C coatings with fully formulated oils in boundary lubrication conditions.* Tribology International, 2016. **93**: p. 666-680.
45. He, D., et al., *Improving tribological properties of titanium alloys by combining laser surface texturing and diamond-like carbon film.* Tribology International, 2015. **82**: p. 20-27.
46. Amanov, A., et al., *Improvement in the tribological characteristics of Si-DLC coating by laser surface texturing under oil-lubricated point contacts at various temperatures.* Surface and Coatings Technology, 2013. **232**: p. 549-560.
47. Ding, Q., et al., *Improved Tribological Behavior of DLC Films Under Water Lubrication by Surface Texturing.* Tribology Letters, 2010. **41**(2): p. 439-449.
48. Wang, X., et al., *Picosecond Laser Surface Texturing of a Stavax Steel Substrate for Wettability Control.* Engineering, 2018. **4**(6): p. 816-821.
49. Phillips, K.C., et al., *Ultrafast laser processing of materials: a review.* Advances in Optics and Photonics, 2015. **7**(4): p. 684.
50. Zahid, R., et al., *Investigation of the tribochemical interactions of a tungsten-doped diamond-like carbon coating (W-DLC) with formulated palm trimethylolpropane ester (TMP) and polyalphaolefin (PAO).* RSC Adv., 2017. **7**(43): p. 26513-26531.
51. Kümmel, D., et al., *Tribological behavior of nanosecond-laser surface textured Ti6Al4V.* Wear, 2019. **422-423**: p. 261-268.
52. Takeno, T., et al., *Deposition of DLC film with adhesive W-DLC layer on stainless steel and its tribological properties.* Diamond and Related Materials, 2009. **18**(5-8): p. 1023-1027.
53. Ronkainen, H., et al., *The influence of carbon based coatings and surface finish on the tribological performance in high-load contacts.* Tribology International, 2016. **96**: p. 402-409.
54. Ronkainen, H., S. Varjus, and K. Holmberg, *Friction and wear properties in dry, water- and oil-lubricated DLC against alumina and DLC against steel contacts.* Wear, 1998. **222**(2): p. 120-128.