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Pin-on-Disc Study of Tribological Performance of Standard and Sintered Gear Materials Treated with Triboconditioning Process: Pre-treatment by Pressure-induced Tribo-film formation

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ABSTRACT

Coating is one of the innovative approaches used to improve the wear resistance and load-carrying capacity of surfaces in rolling-sliding contact, such as gears and rolling element bearings. In this study, the tribological performance of standard gear material (EN 16MnCr5) and two kinds of powder metallurgy (PM) gear material (Distaloy AQ + 0.2% C and Astaloy 85Mo + 0.2% C) with and without tribofilms formed by a pre-treatment were evaluated. Specimens treated with the pre-treatment and the substrate is subjected to pin-on-disc tests under boundary lubrication conditions. The friction and wear performance of the two different PM gear materials with the pre-treatment formed tribo-film were compared to RS-RS (EN 16MnCr5 material disc and pin combination) for reference. It was found that the pre-treatment lowers the friction coefficient and enhances the wear resistance of pins because of the tribo-film formed. The tribo-film caused good running-in due to the existing of WS_2 and Fe and W oxides. Mo-Mo (Astaloy 85Mo + 0.2% C material disc and pin combination) and Mo-RS (Astaloy 85Mo + 0.2% C disc and EN 16MnCr5 pin combination) showed statistically significant higher wear resistance.

Keywords: Gear material, Powder metallurgy, Pre-treatment, Wear, Friction

INTRODUCTION

Surface coating technology provides lower friction coefficients, higher load capacities, and higher protection against surface failures and is an important way to achieve improved tribological performance in gear transmissions (Almaro RI et al.(1); Moorthy and Shaw; (2); Jiang(3); Lu et al.(4)). Physical vapour deposition (PVD) using such coatings such as TiN, WC/C, and DLC (diamond-like carbon) provide low friction coefficients, good wear resistance, and heavy load-carrying capacities and are potential candidates as gear coatings (Kalin(5); Vera EE(6); Wänstrand(7)). By performing efficiency tests using a back-to-back FZG test rig, (Andersson et al. (8)) showed that PVD-coated gears lead to high efficiency. All these studies focus on the tribological properties of hard coatings in rolling-sliding contacts such as gears and rolling element bearings. The tribo-film formed using the triboconditioning process is softer and cheaper compared with these coatings, and is good for running-in (Zhud (9)). (Heinrichs et al.(10)) investigated the influence of the triboconditioning process on three underlying substrates (Mahle E3224, EN Cf45 and EN-GJS-500-7) as well as the morphology and composition of the tribo-film formed. (Zhud et al. (9)) showed that the triboconditioning process leads to a smoother surface with a significantly reduced coefficient of boundary friction and improved wear resistance and load-carrying capacity for rocker arm shafts, camshafts, and cylinder liners. It is noteworthy that the loads used in the tested conditions were in general lower than those common in high-performance rolling-sliding contacts such as gears.

Porosity influences the mechanical properties of sintered steels (Hoffmann (11); Fleck NA (12); Bocchini (13)). (Li et al. (14) used a pin-on-disc experiment to investigate the tribological properties of two different PM materials in boundary and mixed lubrication conditions simulating the contact conditions of the FZG gear test setup. A standard gear material and a PM gear material treated with the pre-treatment operating under contact conditions simulating a gear contact have not so far been studied in detail. In this study, the tribological performance of standard gear material (EN 16MnCr5) and two kinds of PM gear material (Distaloy AQ + 0.2% C and Astaloy 85Mo + 0.2% C) with and without the pre-treatment were evaluated by pin-on-disc experiment under boundary lubricated conditions. The objective is to determine whether the tribo-film formed in the pre-treatment can enhance certain tribological properties of the contact surfaces for further application in gear transmissions.

EXPERIMENTAL SET-UP

Pin-on-Disc machine

Pin-on-disc tester was used to study the characteristics of materials, lubricant and so on. Leonardo Israel Farfán-Cabrera et al.(15), Masoud Hashemi(16) and Akshay A. Joshi(17) studied the characteristics of lubricant, materials and coatings by doing pin-on-disc experiment respectively. A pin-on-disc machine was used to simulate the sliding part of a gear contact in this study. The configuration of the pin-on-disc machine is shown in Fig. 1. The pin-on-disc machine comprised a horizontal rotating disc and a calibrated deadweight-loaded pin. For these tests, the tip of the pin was a non-rotating half sphere with a radius of 5 mm. The friction force and vertical displacement of the pin were automatically measured in the pin-on-disc machine

using a load cell and a linear variable differential transformer (LVDT). For all experiments, the maximum contact pressure was 1.08GPa, which is the Maximum Hertzian contact pressure of load stage 7 in an FZG gear test rig (FZG Basic Training Documents (18)). Before the experiment, all specimens were cleaned in an ultrasonic bath, rinsed in heptane, then rinsed in methanol, and finally dried in an oven. A syringe with a brush continuously applied filtered ambient temperature lubricant with the aid of a pneumatic system. The lubricant is for heavy trucks with EP additives.

The test specimens

The pin and disc specimens were manufactured from three gear materials: one standard steel and two PM gear materials. The chemical composition of the materials is shown in Table 1. RS, AQ and Mo will be used in the remainder of this paper to identify the tested materials: EN 16MnCr5 (RS), Distaloy AQ + 0.2% C (AQ) and Astaloy 85Mo + 0.2%C. Both PM materials had the same density (7200 Kg/m^3) and were sintered for 45 minutes at 1120°C in 90% nitrogen and 10% hydrogen atmosphere. The sintered materials are porous, and how they are manufactured determines their porosity and thus their density and mechanical properties. According to Beiss (19), the elastic properties of PM steel materials can be calculated using the following formulas:

$$E = E_o \left(\rho / \rho_o \right)^{3.4} \quad (1)$$

$$\nu = \left(\rho / \rho_o \right)^{0.16} (1 - \nu_o) - 1 \quad (2)$$

where ρ_s , E_s , and ν_s are the density, Young's modulus, and Poisson's ratio, respectively, of solid steel. The mechanical parameters of the RS and the two PM materials calculated by equation (1) and (2) are presented in Table 2. Fig. 2 presents a photograph of the disc and pin samples used in the present experiments. All the specimens were case hardened. The tip of the pin is in the shape of half sphere with radius of 5 mm. The lubricant used was BP Castrol Syntrans 75W-80. Table 3 shows the specifications of the lubricant. To simulate the sliding part of the contact correctly, the surface roughness of the disc and pin was close to that prescribed for gears in DIN quality level 5 (ISO (20)).

Pre-treatment Process

The triboconditioning process (pre-treatment) combines extreme pressure mechanical treatment of the component surface with a tribo-chemical deposition of a film based on tungsten disulphide. Fig. 3 shows the procedure for the pre-treatment. A tool is pressed and slid against the disc in the presence of a special process fluid. As the tool passes over the surface it triggers a tribo-chemical reaction within the process fluid which gradually deposits a tribo-film on the surface of the component. The pressure applied on the tool also leads to a burnishing effect as some of the asperities on the surface are reduced and the valleys are gradually filled with the compound. In this experiment only the disc was coated because it was difficult to apply the special procedure to the pin tip given its hemispherical shape.

Fig. 4 shows the 3D surface roughness and amplitude parameters S_a and S_z of RS material discs without and with the pre-treatment as representative. The results show that the surfaces

become slightly smoother after the pre-treatment. It should be the same for AQ and Mo material discs because the surface manufacture method is the same for all discs. Fig. 5 shows the porosity structure of AQ and Mo pins near the tip. The porosity is a natural part of PM materials. Note that there are lots of porosities both on the surface and in the bulk material; more information is available in [14]. Porosities on or near the surface influence the friction and wear coefficients [14]. The arrows in Fig. 5 indicate the pin surface. Fig. 6 shows the metallurgical microstructure of Mo and AQ materials. The microstructure of Mo consists of martensite. The AQ microstructure is martensite with some bainite and single austenite grains probably linked to the undissolved nickel.

Test procedure

Table 4 shows the pin-on-disc test matrix. A and B will be used in the remainder of this paper to identify different material combinations. A is the material of the disc, and B is the material of the pin. Each test was performed twice to ensure repeatability.

Calculation of Friction and Wear Coefficients

The friction coefficient was calculated from the measured friction force divided by the normal load exerted on the pin by the testing machine's deadweight. Archard's wear model was used to calculate the wear coefficient:

$$\frac{V}{S} = KN \quad (3)$$

where V is the volume loss in m^3 on the contact surface of pins. S is the sliding distance in m, K

is the specific wear coefficient ($\frac{\text{m}^2}{\text{N}}$), and N is the normal load in N. Reformulating this gives:

$$K = \frac{V}{NS} \quad (4)$$

The wear scar diameter was measured using optical microscopy in the ordinate and abscissa directions at the end of each test. The volume removed from the pin surface can then be calculated using the following method. The main parameters used in calculating the volume loss are shown in Fig. 7. The volume loss, V , of the pin, which is half spherical in shape, is calculated by:

$$V = \pi h^2 \left(r - \frac{h}{3} \right) \quad (5)$$

Where d is the diameter of the wear scar, r is the radius of the half sphere, and h is the height of the wear volume, which can be calculated as:

$$h = r - \left(r^2 - \left(\frac{d}{2} \right)^2 \right)^{\frac{1}{2}} \quad (6)$$

Note that the height of wear scar was also measured by LVDT of pin-on-disc equipment. But for lubricated contact the height of it is usually from around 2 to 4 μm . The deviation of LVDT (0.2 μm) and the heat expand of materials should influence the results of LVDT greatly. So usually the height of wear scar of pin is calculated and the same method was adapted by Li (14) and Damoon Sohrabi Baba Heidary (21).

GD-OES measurement

The parts of disc samples both with and without the pre-treatment were analysed by glow discharge optical emission spectroscopy (GD-OES) in order to determine the chemical components of the coating (Bengtson (22)). The sample forms the cathode in a low-pressure glow discharge lamp (GDL), designed for spectral analysis of flat samples.

The sample seals against a 12 mm O-ring on the lamp front. Positively charged argon ions strike the sample surface, which is typically sputtered at a rate of 20–100 nm/s. The sputtered material is atomized and diffuses into the plasma, where the atoms are electronically excited and emit element-specific optical emissions. The emissions are recorded as a function of time by a multichannel optical spectrometer with a maximum sampling frequency of 300 Hz. This provides time-intensity elemental depth profiles. This test methodology has been previously used to evaluate environmentally adapted lubricants by Bergseth et al., (23), biological layers on rails Olofsson (24) and roller bearing lubricants by Olofsson and Dizdar (25).

Surface analysis

After the test, the tested specimens were measured using a Taylor Hobson Form Talysurf with tip radius of 2 μm to determine the surface roughness and amplitude parameters of the contacting part of the pin and disc specimen. A micro-hardness tester (Matsuzawa MMT-7) was used to determine the hardness profiles of the pin and disc specimens. The metallurgical microstructure of the pins was also examined to study the metallurgical difference between AQ and Mo.

ANOVA analysis

Analysis of variance, or ANOVA (Andersson (26)), was used to determine whether there was a statistically significant difference between the samples. We used the function `Anova2(X, 1)` in Matlab for a two-factor (material combination and pre-treatment used or not) analysis of variance. X is a matrix with two columns (Wear or friction coefficient data of substrate and disc with pre-treatment) and six rows (six different material combinations). After solving the wear/friction coefficient data by `Anova2(X, 1)`, we obtain two p values: p_T is the p value of the pre-treatment, and p_m is the p value of material combination. By determining whether p_T or $p_m < 0.05$, we can judge whether the pre-treatment or the material combination has a statistically significant effect on wear and friction.

RESULTS

Surface Analysis

Hardness measurements were made near the tip of the new pin specimens ($HV_{0.1}$). The hardness–depth curve shown in Fig. 8 indicates that the RS material is harder than both the AQ and the Mo material. In addition, the Mo material is harder than the AQ material above a depth of 0.5 mm. The hardness of AQ, Mo, and RS pins decreases with increasing depth. At the meantime, the hardness of discs was measured and the results were shown in Table 5. The main wear is happened on pins (will be explained in details later), so just the hardness of disc surface is measured instead of the hardness–depth curve. Fig. 9 shows the 3D surface roughness of the worn pin tips. Again the pins combined with discs treated with pre-treatment have smoother surfaces than the others. Fig. 9 from (a') to (f') shows somewhat smoother

surfaces than (a) to (f). To analyse the surface roughness differences after experiment, the pin contact surfaces were also characterized by amplitude parameters S_a and S_z as shown in Table 6. Fig. 10 shows the 3D surface roughness and 2D profile of some wear tracks as representatives on the discs. Fig. 11 shows the micrographs of some wear tracks on disc as representatives. From 3D surface roughness and 2D profile of wear tracks we can not see wear tracks clearly on the disc. As shown in Fig. 11, we can see wear tracks clearly but the tracks left by manufacture method is heavier and most parts of tribo-film was worn off after the experiment. So in lubricated pin on disc experiment wear on the disc can be neglected.

Wear results

Table 7 shows the diameter of the wear scar of worn pin tip. The wear scars of pins are usually a circle. The diameter is the average value of the diameters in two vertical directions. The experiment was repeated for two times so the diameters are shown as first and second time values. The wear coefficient results are calculated as described in 2.4.2 and presented in Fig. 12 as mean values and standard deviations for the different test conditions (Table 4). For the same disc and pin material combinations, pins combined with discs treated with the pre-treatment always have lower wear coefficient. The low wear coefficient for the tests with Mo pins in contact with Mo discs is also noticeable.

Friction results

To obtain an overview of the test results, we present the mean values with standard deviation of all the tests in Fig. 13. The pins combined with discs subjected to pre-treatment show somewhat lower friction coefficients than the untreated cases. Since the pre-treatment is

designed for good running-in, the friction coefficients for the first five minutes, first stage (the first hour) and the last stage (the last hour) are also shown in terms of mean value and standard deviation in Fig. 14. This shows a clear running-in tendency for all tested combinations, but the change in friction coefficient is less dramatic for materials treated with the pre-treatment.

Chemical composition of the tribofilm formed by the pre-treatment

Fig. 15 compares the chemical composition of the tribo-film formed by the pre-treatment and the substrate. The GD-OES analysis was limited to iron, oxygen, carbide, sulphur, and tungsten. The percentage of sulphur is multiplied by five in order to better show the difference before and after pre-treatment. The obvious difference is that after the pre-treatment there is much more tungsten and sulphur than is present in the substrate. From Fig. 15 we can infer that the thickness of the tribo-film is 80 to 100 nm. Zhmud (27,28) studied the elemental composition of the tribofilms generated by the triboconditioning process by X-ray photoelectron spectroscopy and energy dispersive X-ray spectroscopy which had the same results as shown in Fig. 15.

ANOVA analysis results

The values $\bar{p}_T$ and $\bar{p}_m$ are derived from the wear coefficient, friction coefficient and surface amplitude parameters of pin respectively. Table 8 shows the ANOVA results of all the data. Table 8 The ANOVA results of wear coefficients, friction coefficients and pin surface amplitude parameters $\bar{s}_a$ and $\bar{s}_z$.

DISCUSSION

Wear discussion--effect of the pre-treatment on wear

The wear results in Fig. 12 show that pins run against discs treated with pre-treatment almost always have a lower wear coefficient than pins run against the same pin and disc material that has not been treated. This agrees with the trend presented in [9]. The improved wear is closely related to the pre-treatment. Pre-treatment combines extreme pressure mechanical burnishing with tribo-chemical deposition of a friction and wear-reducing compound on the component surface. As shown in Fig. 4a and b, the applied pressure leads to a burnishing effect as some of the asperities on the surface are levelled off and the valleys gradually filled with the friction-reducing compound. The smoother surface provide conditions for better running-in, which is good for both friction and wear in the stable stage, as is manifested by the 3D surface roughness of pins. Tables 8 showed the p values for both S_a and S_z . For S_a $p_T = 0.003$, $p_m = 0.38$ and for S_z $p_T = 0.018$, and $p_m = 0.212$. Both p_T values of S_a and S_z are less than 0.05. This shows that the pre-treatment has a statistically significant effect on the surface amplitude parameters, but the material combination has no effect on the surface amplitude. Figs. 4a and b showed that the pre-treatment made the treated surface of disc smoother than that of the substrate disc. As shown in Fig. 9 and Table 6, the surface of pins combined with discs with pre-treatment is always smoother than that of substrate pins. So the extreme pressure burnishing of pre-treatment is one of the factors enhances the wear resistance of pins.

The GD-OES measurement showed that the tribo-film contained Fe, O, W, S, and some C. Previous studies by Podgornik et al. (Podgornik(29); Podgornik(30); Podgornik(31)) have

shown that a low friction reaction film, a tribo-film WS_2 , can form on steel surfaces during sliding, when used in a sulphur and tungsten rich environment. The pre-treatment method used mineral oil carrying tungsten source by sorgano-tungstates and sulphur source by organic-polysulfides (Zhud (32)), so that can undergo the following transformations in the tribo-contact between the tool and the disc.

R and R' stands for an organic radical, such as alkyl or aryl. That is to say the pre-treatment results in the formation of a tribo-film of 80–100 nm thick composed of tungsten, iron, oxygen, sulphur and carbon as shown in Fig. 15. So there should be some WS_2 in the tribofilm. WS_2 has a lamellar structure, analogous to graphite and MoS_2 , and is an efficient solid lubricant for both friction and wear. Fig. 15 showed that the tribo-film is mainly composed of Fe, O, and W, with minor C and S (around 6%), which means the amount of WS_2 cannot be high. (Erdemir (33)) showed that Fe and W oxides may offer more easily sheared surface layers. So, even in cases where the amount of WS_2 is not high, the tribofilm contains Fe and W oxides, which may also offer more easily sheared surface layers than the untreated steel. The easily sheared layers composed of WS_2 , Fe, and W oxides act as a solid lubricant, which can enable good running-in. The existence of these oxides could be another reason for the higher wear resistance of pins sliding on discs treated by pre-treatment. The beneficial effect of the tribo-film in regard to wear resistance and running-in suggests that the pre-treatment can be applied in gear transmissions. Further study will be performed in a gear wear experiment.

The influence of materials and material combinations on wear

As shown in Fig. 8, the Mo pins always have higher wear resistance than the AQ pins. This may be due to the higher hardness of Mo and its microstructure. Given that higher hardness usually implies higher wear resistance, the higher wear resistance of Mo is understandable. Fig. 6 shows the microstructure of pins of Mo and AQ. The Mo microstructure consists of martensite. In the case of the AQ, the microstructure consists of martensite with elements of bainite and austenite grain, probably linked occasionally to undissolved nickel. Martensite have higher hardness and wear resistance than austenite and bainite. So pins of Mo have higher wear resistance than those of AQ mainly because of the martensite microstructure caused higher hardness. The RS-RS material combinations always showed higher wear coefficients than the AQ-RS and Mo-RS combinations. As different material combinations can prevent adhesive wear (Beek (34)). This is probably why the RS-RS combination always shows higher wear coefficients than AQ-RS and Mo-RS. The same is true for the pins of AQ-AQ and RS-AQ combination.

The high wear resistance of Mo-Mo and Mo-RS suggests that they might be used in gear transmissions, subject to further studies in full-scale gear tests such as those using an FZG machine.

The influence of the pre-treatment on friction

Table 8 shows the results of applying the anova2 function to the friction coefficient data of the whole experiment (Fig. 13): $P_T = 0.004 \ll 0.05$, $P_m = 0.59$. Thus the pre-treatment has directly influenced the friction coefficient, but the material combination has little effect. Fig. 13 shows that the friction coefficients of pins combined with discs treated with the pre-treatment exhibit somewhat lower friction coefficients than the others, independent of material combinations. In order to determine the friction mechanism, the friction coefficient of the first five minutes, the first hour stage and the last hour stage are also shown in Fig. 14. The ANOVA results of them are shown in Tables 8.

As shown in Fig. 14 for the first five minutes, first and last stages, the friction coefficients of discs with the pre-treatment are always lower than those of discs without pre-treatment. The related P_T values are 0.0148, 0.0165, and 0.005 respectively as shown in Tables 8. As they are all far less than 0.05, the pre-treatment process has had a statistically significant effect in reducing the friction coefficient in all stages of the experiment. The smoother surface (compare Fig. 4a and b) caused by the high pressure and the formation of WS_2 and Fe and W oxides contributes to the lower friction coefficient of pins combined with discs treated by the pre-treatment in the first five minutes and the first stage. Smoother surfaces always lead to a lower friction coefficient. For the last stage, the lower friction coefficient of pins combined with discs with the pre-treatment is due to the good running-in caused smoother surface of the pins. As shown in Fig. 9 and Table 6, surfaces of pins combined with discs treated with the pre-treatment are always smoother than those with only the substrate combination.

CONCLUSION

The sliding part of a gear tooth contact was simulated in pin-on-disc experiments. The friction properties and wear resistance of two PM steel gear materials and a regular steel gear material with and without pre-treatment were investigated and compared. The following conclusions can be drawn from this study:

- The pre-treatment enhances the wear resistance and lowers the friction coefficient of pins because of the formation of WS_2 , Fe and W oxides enabled good running-in and the brushing effect enabled smoother surface.
- Mo-Mo and Mo-RS combinations show statistically significant higher wear resistance compared to RS-RS and can be used in further gear transmission studies.

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NOMENCLATURE

PM	Powder Metallurgy	ρ, ρ_0	Density
RS	EN 16MnCr5	E, E_0	Young's modulus, Gpa
AQ	Distaloy AQ+0.2%C	ν, ν_0	Poisson's ratio
Mo	Astoloy 85Mo +0.2% C	α	Pressure viscosity coefficient, (Pa^{-1})
η	Dynamic viscosity, (Pas)	V	volume loss, m^3
A–B	disc-pin	T	Time, s
N	Load, N	S	Sliding distance, m

Fig. 1 Configuration of pin-on-disc machine

Fig. 2 Disc and pin specimens

Fig. 3 Procedure for the pre-treatment

Fig. 4 3D surface roughness of RS material discs (a) substrate, (b) after the pre-treatment

Fig. 5 Porosity structure of AQ (a), Mo (b) pins and (c) porosity structure and metallurgical microstructure measurement region.

Fig. 6 Metallurgical microstructure of AQ (a) and Mo (b) pins

Fig. 7 The wear scar.

Fig. 8 Hardness–depth curve of RS, Mo, and AQ pin tip

(a) RS-RS

(b) AQ-RS

(c) Mo-RS

(d) Mo-Mo

(e) AQ-AQ

(f) RS-AQ

(a') RS-RS

(b') AQ-RS

(c') Mo-RS

(d') Mo-Mo

(e') AQ-AQ

(f') RS-AQ

Fig. 9 3D surface roughness of the worn pin tip, a-f: sliding on disc without pre-treatment; a'-f': sliding on disc with pre-treatment

(a) RS-RS

(b) AQ-RS

(c) Mo-RS

(a') Mo-Mo

(b') AQ-AQ

(c') RS-AQ

Fig. 10 3D surface roughness 2D profile of wear tracks on the disc. (a, b, c: disc without pre-treatment; a', b', c': disc with pre-treatment)

Fig. 11 Micrographs of wear tracks on disc (a, b, c: disc without pre-treatment; a', b', c': disc with pre-treatment)

Fig. 12 Wear coefficient results in terms of mean value and standard deviation

Fig. 13 Friction coefficient results in terms of mean value and standard deviation of the total experiment

Fig. 14 Friction coefficient results in terms of mean value and standard deviation of the first five minutes (a), first stage: first hour (b), last stage: last hour (c)

Fig. 15 GD-OES evaluated chemical composition of the tribo-film formed by pre-treatment

	Ni	Mn	Fe	C	S	P	Si	Cr	Mo
EN 16MnCr5	—	1–1.3	96.95–98.78	0.14–0.19	≤0.035	≤0.025	0.4	1.1	—
Distaloy AQ	0.5	0.5	98.8	0.2	—	—	—	—	—
Astaloy Mo	—	—	98.95	0.2	—	—	—	—	0.85

Table 1. Chemical composition (mass %) of RS and AQ gear materials

Specimen materials	RS	AQ	Mo
Young's modulus (GPa)	210	154	154
Poisson's ratio	0.3	0.28	0.28

Table 2. Characteristics of the specimens

Lubricant	BP Castrol Syntrans 75W-80
Kinematic viscosity at 40°C (cSt)	64.1
Kinematic viscosity at 100°C (cSt)	11.8
Density ($\frac{kg}{m^3}$)	837
Viscosity index, η (-)	183
Phosphorus content (ppm)	300
Sulphur content (ppm)	890
API Category	GL-4

Table 3. Test Lubricant

		Sliding speed (m/s)	Load (N)	Maximum Hertzian contact pressure (Gpa)	Duration (h)
Without Pre-treatment	RS-RS	0.1	12.5	1.08	12
	AQ-RS		17		
	Mo-RS		17		
	AQ-AQ		23		
	Mo-Mo		23		
	RS-AQ		17		
With Pre-treatment	RS-RS	0.1	12.5	1.08	12
	AQ-RS		17		
	Mo-RS		17		
	AQ-AQ		23		
	Mo-Mo		23		
	RS-AQ		17		

Table 4 Pin-on-disc test matrix

	Material	Hardness (HV 10)
Without pre-treatment	RS	900
	AQ	704
	Mo	816
With pre-treatment	RS	896
	AQ	703
	Mo	810

Table 5 Hardness of discs

Material combination		RS-RS	AQ-RS	Mo-RS	Mo-Mo	AQ-AQ	RS-AQ
Sa (μm)	Substrate	0.25	0.26	0.25	0.29	0.3	0.21
	Pre-treatment	0.18	0.21	0.17	0.12	0.19	0.14
Sz (μm)	Substrate	1.73	2.79	1.56	1.8	1.09	1.88
	Pre-treatment	1	1.42	1.1	1.1	1.14	1.2

Table 6 Three dimensional surface roughness parameters for pins

Wear scar diameter (μm)			
		First time	Second time
Disc without pre-treatment	RS-RS	455.5	409
	AQ-RS	422	397.5
	Mo-RS	317	318.5
	Mo-Mo	361	323
	AQ-AQ	537	427
	RS-AQ	429	494
Disc with pre-treatment	RS-RS	360	324.5
	AQ-RS	366.5	335.5
	Mo-RS	303	242.5
	Mo-Mo	261.5	257.5
	AQ-AQ	520	410
	RS-AQ	422	397.5

Table 7 The diameter of the wear scar of worn pin tip

		Whole			Surface	
	Wear	friction	First five	First	Last	Surface
	coefficient	coefficient	minutes	stage	stage	amplitude
						parameters of Sa
						parameters of Sz
p_T	0.0064	0.0044	0.0148	0.01	0.005	0.0034
p_n	0.0007	0.59	0.607	0.73	0.475	0.39
						0.21

Table 8 The ANOVA results of wear coefficients, friction coefficients and pin surface amplitude parameters Sa and Sz