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Surface Hardening Treatment of Steel: A Review

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ABSTRACT

Tribology is study of friction, wear and lubrication. It is a core technology in almost all mechanical systems including bio medical application. Wear and friction are the most common problems in almost all mechanical contacts and due to that economic losses occurs. This paper represents the reviews of different papers that are mainly focused on study of tribological properties and to improve it by different techniques such as coatings, heat treatments, severe plastic deformation, addition of alloying elements, lubrication etc. It also includes the different methods of wear measurement like pin on disc, abrasive wear tester and block on wheel.

1. Introduction

Surface treatment is an industrial process that alters the surface of a manufactured item to achieve a certain property. Application of surface treatment is gaining momentum because of its many uses. It is being used to improve the hardness, to prevent corrosion, for obtaining good surface finish, for decoration purposes, etc. The surface hardening processes include flame hardening, induction hardening, electron beam hardening, and laser hardening.

There has been a considerable impact of friction and wear on the consumption of energy and economic expenditure globally. A recent study conducted by Kenneth Holmberg and Ali Erdemir show that nearly 23% of the world's energy consumption comes from tribological contacts, out of which 20% is to overcome friction and 3% to remanufacture worn parts and spare equipment due to wear. With the help of new technologies for friction reduction and wear protection, energy loses could be reduced by 40% in the long term which could increase the savings amount to 1.4% of GDP. Because of the pressing need to overcome these difficulties, the study of tribology has become extremely important. (1)

"Tribology is an interdisciplinary field which involves the design of components with static and dynamic contacts which encompasses friction, wear, lubrication for a required performance and reliability". The problem arises when the severe plastic deformation methods increase the hardness significantly which should in turn increase the wear resistance. This wear resistance depends on many tribological factors such as the material of counter specimen, loading mode, and environment (lubricants). There are three known wear mechanisms:

1) Elastic deformation: There can be nucleation and growth of fatigue cracks if the protrusions come to their initial original shape after deformation.

2) Protrusion shearing: It happens when the shear stress concentration is too high to nucleate and propagate the cracks.

3) Plastic deformation: There is change in the shape of protrusions because of the local stress concentration and due to this, there maybe brittle cracking because of accumulation of strain and local strengthening. It can also lead to increase the risk of adhesive wear. (2)

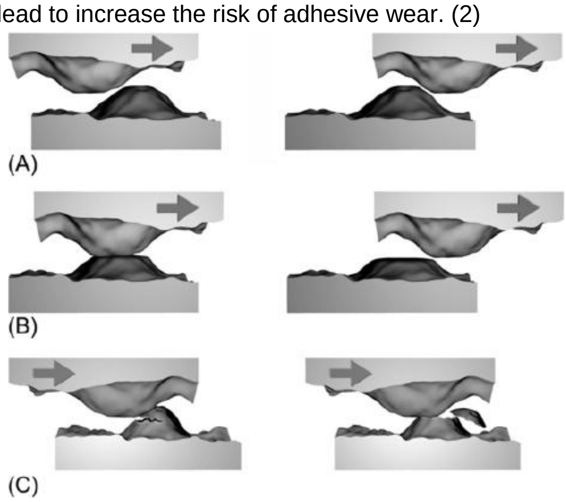


Figure 1: Diagrams of wear mechanisms: (A) elastic deformation, (B) plastic deformation, (C) protrusion shearing.

Some of the wear types are:

1) Adhesive wear: It occurs when the atomic forces between the materials are stronger than the strength of one of the materials

2) Abrasive wear: There is a material displacement to the sideways when there sliding of the hard-rough surface over a softer surface.

3) Fatigue wear: This failure occurs through pitting or spalling.

The wear test is done to determine how much the material is removed. It includes measurement of friction coefficient, wear loss (volume, mass/weight, linear wear), wear rate, examination of wear surface and its morphology. (2)

Table-1
Wear measurement methods and typical units for wear quantification

	Measurement methods	Units of wear	Units of wear rate
Mass loss	1) Direct measurement by a precision balance 2) Calculated from Volume loss for known density material.	µg g	µg/m, g/m, µg/N, g/N, µg/(N.m), g/(N.m)
Volume loss	1)Calculated from depth, width, wear profile and/or other dimensions data of a wear track. Surface profilometry or microscopy techniques can be used for the measurement. 2)Calculated from mass loss for known density material.	mm^3	mm^3/m, mm^3/N, mm^3/ (N.m)
Linear dimension	1) Direct measurement by surface profilometry, microscope and other dimension measurement techniques.	µm mm	µm/year, mm/year

There is no direct correlation of wear with friction as is the common conception. There may be conditions such that low friction can result in significant wear and vice versa. In order for this phenomenon to occur, certain implementation times are required, which may change depending on some variables, such as load, speed, lubrication and environmental conditions, and there are different wear mechanisms, which may occur simultaneously or even combined with each other.

An apparatus for wear testing is termed as wear tester, tribotester or tribometer. The prefix of "tribo-" refers to wear, friction and lubrication. A wear tester always involves two components loaded against and relatively moving each other. The material or component being investigated is normally referred to as specimen, the other termed as counter face. (3)

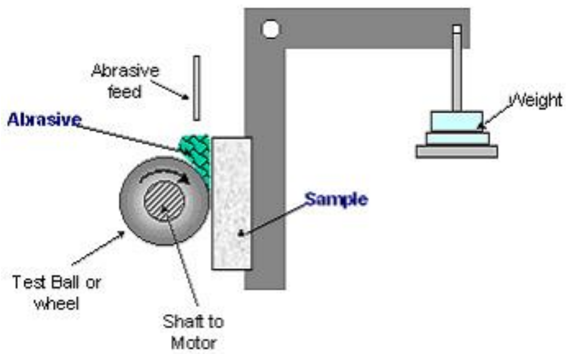
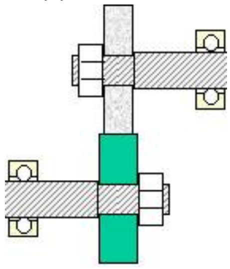
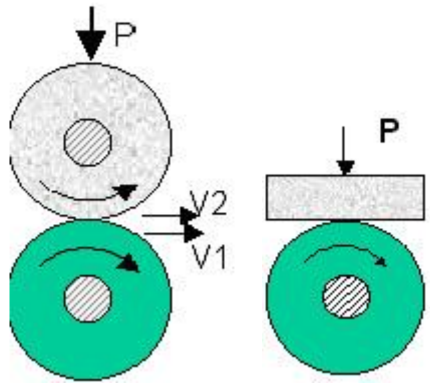


Figure 2: Type 1: An abrasive wear tester

This figure shows the mechanism of an abrasive wear tester. In the presence of abrasive materials, the test ball or wheel is shown to rotate against a permanent block. A dead weight is used to control the contact pressure. The abrasive material is fed through a feeder. The wear loss is measured after a determined time. (3)



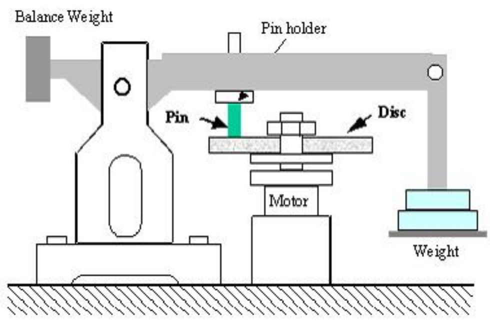
a) Wheel-on-wheel



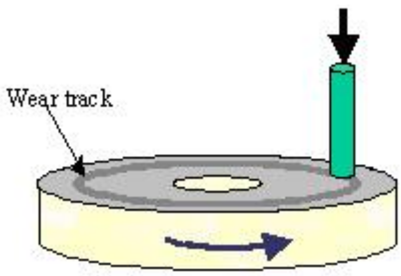
b) Block-on-wheel

Figure 3: Type 2: A rolling sliding wear tester

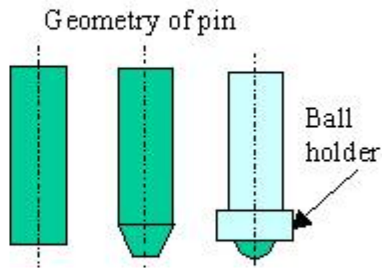
The wear and frictional properties of materials can be understood by the rolling-sliding wear tester. Under a constant load, two wheels are fixed to two parallel shafts (2(a)). The linear speeds of the wheels are controlled in such a way that at the point of contact, there is equal speed to achieve a pure rolling condition. When one of the two specimens are fixed, then it is a pure sliding wear, and when both the wheels are kept rotating but at different speeds, a rolling-sliding condition is achieved. (3)



a) pin-on-disc-machine



b) arrangement on samples



c) geometry of pin

Figure 4: Type 3: A pin-on-disc wear tester

The properties like friction and wear can be evaluated by the pin-on-disc wear tester. A circular wear path is described when a pin is loaded against a flat rotating disc. The pins having various geometries can be used. Alumina, tungsten carbide or bearing steel can be used as a ball and hence the name ball-on-disc is used. (3)

2. Literature Review

Two rods of low carbon (0.1%) and medium carbon (0.45%) steel were taken. Specimens were having 20 mm diameter and 100 mm length. They were first hot rolled then heat treatment was carried out at 880^0 C for 1 hour to relieve stress and produce homogeneous structure followed by water quenching. Tempering was done at 600^0 C for 1.5 hours. After this, SPD (severe plastic deformation) in which ECAP (multi-cyclic equal-channel angular pressing) process was carried out in channels having 120 angles at 400^0 C temperature to produce strain. The results were as follows: It has been shown, in a low-carbon steel sample, SPD by ECAP produce grain structure refinement which will lead to increase in strength of low-carbon steel, and decrease the total friction coefficient and its molecular component. In case of steels having high carbon content, heat treatment without subsequent SPD processing will sufficiently increase strength. This is confirmed by the studies conducted on a medium - carbon steel. (4)

The M50 steel using WS2 (MW) was investigated at different temperatures that are room temperature, 200, 400, 600 and 800 °C at constant load of 12N with sliding speed of 0.2m/s then XRD, EPMA, FESEM, and EDS mapping were conducted. The results showed that due to the formation of lubricating tribo-films on worn surfaces, friction coefficients of MW were decreased by 13.51% as compared to that of M at 800 °C. In MW, at 800 °C temperature, friction recorded at its minimum value of 0.29 and showed best results in its tribological properties. (5)

To study the different mechanisms concerning friction and wear, the experiment was carried out on the hot forming tool steel and ultra-high strength boron steel. The operating temperature was seen to have a profound impact on friction and wear properties of both the materials. Plasma nitriding proved effective in the reduction of friction and wear at high temperatures. The use of coating had different effects on tool steel and UHSS. It had prominent effect on the surface modification of UHSS as compared to the tool steel. At moderate temperatures, MoS2-Ti coating had a good potential but its properties decreased at elevated temperatures. (6)

It was understood that the vegetable oils could be a good alternative to the mineral oil-based metal working fluids (MWFs). Although the vegetable oil has a limited thermal and oxidative stability, it increased the properties like surface quality, heat dissipating ability by reducing the tool wear and the cutting force. (7)

The etched mild steel sample underwent the pin on disc test, wear test by changing the load and velocity of disc. The coefficient of friction was found to decrease up to 0.0645 at 3kg load and the maximum went to 0.08154. The coefficient of friction decreases (0.0280) and then increases (0.04587). the specific wear rate increases with velocity and load up to 4.5kg and then decreases. Because of the insufficient use of lubrication in wear testing and the debris between pin and disc, the uniform increase in specific wear rate was hampered. (8)

Specimens were made of SCM415, cylindrical in shape. They had been subjected to different heat treatments before the friction tests. Ultrasonic cleaner using acetone was used for cleaning the specimens. After that it was put in the position in the tester. The dynamic variation of friction coefficient was measured during each test and wear particles were examined under SEM. The depth of the wear track was also calculated. The friction coefficient of the specimen with carburizing-nitride was smallest. Wear resistance was decreasing in order in the case of carburizing-tempering than carburizing-nitride and nitride-carburizing-tempering. (9)

The tribological properties of steel/steel, copper/steel, aluminum/steel pairs were measured at 100°C and room temperature by studying the chemical and physical properties of Ionic liquid (IL). Also, copper strip corrosion test and accelerated corrosion test were conducted to find the corrosion resistance. The synthesized IL BTAP4444 was found to have better characteristics than the commercially available oil PAO 10 and traditional bmimBF4. (10)

The tribological performance of Al390-T6, Gray C.I., Mn-Si brass were studied under some lubrication conditions, in CO2 atmosphere. The scuffing resistance was measured by increasing the load up to its failure at room temperature. It was found that the scuffing property of Gray C.I. and Mn-Si brass were better than Al390-T6. In Mn-Si brass, scuffing resistance is dependent on the Pb content in the matrix which later on melts and acts as a lubricating material. In Al390-T6, the cracks propagate to the surface when the primary Si particles break during scuffing. In Gray C.I., there is direct failure of the material as there is propagation of cracks from the corners of graphite flakes. (11)

The alumina coatings were deposited on stainless steel samples using sol-gel method with low annealing temperature to not to degrade the metal substrate. Sol-gel was adapted by adding ceramic powder or by successive layers deposition by which several micron thick coatings could be obtained which helped to reduce stresses occurring in coatings during heat treatment. Morphological features, microstructure, hardness and the tribological behavior and wear resistance of obtained layers were measured. Results are as follows: XRD and SEM analysis shown that chemical composition and crystalline structure of alumina coating prepared at 500°C were different from those prepared at 700°C. The microstructural analysis had shown that this coating is smooth, homogeneous and compact. The instantaneous and stabilized friction coefficients are reduced by alumina coatings. The wear behavior of sol–gel coatings deposited stainless steel was studied and compared to other antagonists. It showed that hardness of sol-gel coatings was higher than uncoated stainless steel and nitride steel. Pin-disc test showed that alumina layers reduce wear and improve tribological behavior of stainless steel. (12)

The dry sliding wear characteristics of titanium added sintered/forged plain carbon steel (Fe-1%C) is studied. The wear resistance of Titanium is more than that of plain carbon steel. But irrespective of the P/M alloy steels, with the increase in normal applied load, there is increase in the wear losses. The common wear found is the delamination mechanism. There is non-uniform wear of Ti alloyed P/M plain carbon steel, which is because of the presence of hard phase micro elements of alloying elements embedded in the soft ferritic matrix of Fe-C. (13)

Active screen plasma nitriding was carried out on AISI 420 martensitic stainless steel. It was done by placing a test table inside the steel screen. The test table, furnace wall, and the specimens were earthed which form an anodic potential. The treatment was carried out for temperatures ranging from 440 to 520°C, at 400 Pa and 6 hours in NH3 atmosphere. After the characterization by XRD, XPS, AFM, SEM, the results showed that the nitriding done at 440 °C and 6 h, the hardness increased 3.5 times and showed good wear resistance and corrosion resistance properties due to formation of αN and ε-Fe2–3N nitride phases on the surface. At 520 °C, there was higher wear resistance and hardness as the layer consisted of γ'-Fe4N and CrN phases. Also, it was found that the specimen had better corrosion resistance and wear property from the corrosion and wear tests. (14)

Nickel coatings on carbon steel (4140) substrate were developed using nickel sulfamate bath and Watts nickel bath and the bath parameters were as follows: temperature was 40 °C and the pH was 5, the cathode current density was 3 A/dm2 and time of the deposition was 60 minutes. The evaluation of hardness of the coated surfaces of the specimens was measured according to ASTM E140 and evolution of adhesion of coating was done according to standard ASTM D4541. Corrosion resistance of the coated specimens was evaluated using the anodic polarization method and tribological test was carried out according ASTM G99 standard. The conclusion of experiments is as follows: Thickness of the coating for Watts nickel bath were between 35.25 and 35.75 µm and for nickel sulfamate bath it was between 25.15 to 26.88 µm. Hardness was highest of specimen coated with Nickel Sulfamate bath between 34 % and 48 % higher than the pin specimen coated with Watts nickel bath, and from 33 % to 42 % higher than pin specimen uncoated. In case of Watts nickel bath, it showed good adhesion for loads up to kg/cm2 and 12 kg/cm2 in case of nickel sulfamate bath. (15)

Tool steel specimen were provided in untreated, plasma nitrided and TiAlN coated conditions and UHSS (ultrahigh strength boron steel) sheets were uncoated, Al-Si coated and Al-Si+ graphite coated. The tool steel specimens were rectangular blocks having dimensions 10 mm x 15 mm x 24 mm with a radius of 20 mm and also same with Al-Si + graphite coated. The uncoated UHSS and Al-Si + graphite coated UHSS were heated to 930^0 C in the furnace and retained at that temperature for 180 seconds before each test. The Al-Si coated UHSS was also heated to 930 ^{0} C and retained for 390 seconds in order to allow enough time for the diffusion to take place before testing. The conclusion is as follows: The frictional behavior of tool steel and UHSS pairs can be modified through the use of surface coating and/or treatment applied on surfaces. The surface layer composition of the sheet material (i.e. applying a coating on the sheet) had a much greater influence on the friction level compared to nitriding and/or coating of the tool steel. Plasma nitriding or TiAlN coating of the tool steel results in lower friction and reduced running-in effects compared to untreated tool steel. After running-in, the difference in coefficient of friction is negligible between the different tool steel variants when sliding against the same UHSS material. (16)

The commercial sheets of AISI 304 having dimensions 1.5 x 1.5 x 0.5 cm and commercial rods of AISI 316 were cut in 3 cm diameter and 0.5 cm thick pieces. The samples were mechanically polished by diamond paste up to ¼ µm. Nitriding was carried out in AISI 304 and AISI 316 steels in N2:H2 atmosphere having composition 20:80 and temperatures ranging from 300 to 500 °C. Results showed that, AISI 316 had lower roughness than AISI 304 at high working temperatures (T > 300 °C). AISI 304 and AISI 316 had maximum hardness around 14 Gpa. The wear could be reduced by a factor of six for 300 °C nitriding in AISI 304 and AISI 316. Surfaces treated at 500 °C show high roughness due to the presence of asperities. (17)

The steel discs of 5 different cold work steel which had 40mm diameter and thickness 10mm was made. In heat treatment of these discs it was first quenched and then tempered to get hardness of 60HRC followed by polishing to an average roughness of 5nm and cleaned ultrasonically by ethanol. In further procedure, dry sliding tests were done at 3 different temperature at 25 °C, 150 °C and 250 °C by CSEM high temperature tribometer. In the process, parameter sliding speed was 0.1m/s, normal load was 2N, radius of wear track was 10mm and 50 tracks were performed using austenitic stainless-steel balls having diameter 6mm and hardness of 274 HV1 as counter bodies. Wear volume of discs and amount of material transferred to discs after testing were characterized by SEM and white light interferometry. Wear debris was stuck to a copper strip and characterized using energy-dispersive electron probe microanalysis (EPMA). The results of above experiment were as follows: Friction and wear behavior of cold work steels depends on carbide content, carbide size and carbide distribution in steels. Carbide content reduce adhesive component of friction coefficient thus by increasing resistance against plowing. At room temperature, the adhesion of austenitic slider material to the cold work steels dominates the wear behavior, plowing the austenitic slider and protecting the discs from wear. By increase in temperature plowing action of loose wear debris increase and strength loss cause increase in wear of cold work steel. (18)

Five specimens were used as journal bearing which are $CuSn_{10}$ bronze, $CuZn_{30}$ brass, ZnAl zamac, $AlCuMg_2$ duralumine, and SnPbCuSb white metal and SAE 1050 which were used as shaft. Specimen had dimensions 10+0.05mm inner diameter, 10 mm width and 15 mm outer diameter. These were worn by radial journal bearing wear test rig under lubricated condition (lubrication used is SAE 90 gear oil) and wear losses were measured. The process parameters were as follows: 20 N loads, 1500 rpm for 2·5 h time and measurement done at every 30min. Surface microstructure were observed under optical microscope and SEM. Tensile, compressive, notch impact, three-point bending, radial fracture and hardness were performed using ALŞA type tensile test rig depending on TS-138, and TS- 269 for mechanical properties and hardness was measured using a SADT HARTIP- 3000 type. Result shown that highest friction coefficient and bearing temperature occurred in $CuSn_{10}$ and $CuZn_{30}$ bearings and lowest friction coefficient and bearing weight loss occurred in ZnAl, $AlCuMg_2$ and SnPbCuSb bearings. Highest and lowest bearing wear rate seen in $CuSn_{10}$, $CuZn_{30}$ bearings and ZnAl bearing, respectively. In case of mechanical properties $CuSn_{10}$, $CuZn_{30}$ and $AlCuMg_2$ bearing materials have shown better results than ZnAl, and SnPbCuSb bearing materials. (19)

Nine different Cu-based friction linings had been taken which were produced by pressing and sintering and different samples were obtained by varying amount of Sn (1,2,4,6,8 and 10 wt.%) and SiC particles (0,2,4 and 6 wt.%). To measure the coefficient of friction, sample was mounted and fixed on holder which was connected through string with dynamometer and different normal loads 40, 80, 120 and 160N were applied so that the static and dynamic coefficient of friction could be measured by same dynamometer. Abrasive wear was measured on Taber abraser. Disc was rotated on speed of 60rpm which has outer and inner diameter 89 and 60mm respectively other parameters for abrasive wear testing are as follows: Normal load 1 kg, average tangential velocity of friction lining samples of 0.239 m/s, number of cycles were 400 and sliding distance was 95.8m in dry condition at room temperature and at 40-45% relative humidity. It could be concluded that higher amount of Sn and SiC decreases abrasive wear and the decrease is higher as SiC particle increase. At 10 wt. % Sn (highest) and 6 wt. % SiC (highest), it showed highest values of static and kinetic coefficient of friction and lowest wear rate. It showed that mutual effect of Sn and SiC particles addition kinetic coefficient of friction can be increased up to 1.6 times and wear resistance can increased up to 3.3 times. (20)

HR-150A Rock well tester is used to measure the macro-hardness whereas a micro-hardness tester is used to measure the Vickers hardness. A JB-300B pendulum-type impact testing machine is used to measure the toughness. A pin-on-disk (typeML-100) wear testing machine is used for wear tests. The HSS with M2C or M6C has lower wear resistance as compared with the HSS with VC. It is because VC has good morphology and high hardness which can resist the micro cutting of abrasive particles efficiently. For the fine abrasive wear, the HSS with M2C has lower relative wear resistance than speed steel with M6C and its contrary for coarse abrasive wear. (21)

For the tribological studied AISI 52100 steel (1.05% C, 0.35% Mn, 0.3% Si, 1.5% Cr) was cut into circular disks. The disks were 4.0mm thick and 30mm in diameter. For achieving two different level of surface roughness, specimens were ground with emery paper (600-2500 mesh size) in the four sets of disks, comprising two specimens in each set. For rough and fine samples, the surface roughness was considered to be 0.2 ± 0.05mm and 0.05 ± 0.01mm, respectively. Roughness of the sample was measured by surface texture meter supplied by Taylor Hobson’s (Model Surtronic 25). Metal particles remain unreacted with the nitrogen during the deposition so that defects were produced. For rough and fine samples, the surface roughness of the TiN-coated AISI 52100 bearing steel was in the range 0.26-0.40mm and 0.13-0.28mm, respectively. These values for both types of samples were significantly higher than their substrate surface roughness. It can be seen that the surface roughness of the TiN coatings increases as the coating thickness increases. (22)

The wear tests were performed using the pin on disc method and the grinding (abrasive) wheel. The test machine was equipped to record the pin temperature, the sliding time, the sliding distance and the friction force. Results shown that the strength of the wheel no.1 was lower than that of wheel no.2, so that the wear pattern on the wheel no.1 was more clear and deeper than that of wheel no.2. Therefore, the weight loss of the wheel no.1 was high, subsequently vertical holding of the pin on the wheel was not possible during the test, and the sliding time or distance is restricted. The weight loss and the variation coefficient of mild steel samples were too high (15.5%). In addition, when the mild steel was tested, the vibration of the test setup is high. (23)

The tribological properties of the lubricants for steel/steel contact were investigated on a ball-on-block MFT-R4000 reciprocating friction and wear tester. The upper ball was driven to reciprocally slide at an amplitude of 5 mm against the lower fixed block. The lower blocks were polished by polishing machine to achieve the surface roughness of about 0.05 um before test. The applied load ranges from 50-200N with the frequency of 5 Hz for 30 min at room temperature. Before every tribological test, ultrasonic cleaner was used to cleaned the ball and block with petroleum ether for 10 min and then about 0.5 g of lubricant was introduced into the reciprocating sliding region. The coefficient of friction (COF) was automatically recorded by a computer connected with the tribometer, and three repetitive measurements were taken. After the tribological test, the lower blocks were cleaned ultrasonically for 10 min in bath of petroleum ether. Then, wear width was measured by an optical microscopy (Olympus, Japan). An EVO18 scanning electron microscopy (SEM, Zeiss, Germany), an energy-dispersive X-ray spectroscopy (EDS, Bruker, Germany) and a Raman spectroscopy with 514 nm laser excitation (Renishaw, UK) were employed to obtain the morphologies of the worn surfaces and analyze the wear mechanisms. It had been observed that, M-fly ash and MH-fly ash with good dispersion could effectively adsorb on the sliding surfaces to form a low-shear protective film to improve the tribological properties. All the additive-doped greases had high dropping point and low penetration. PAO with the adding amount of M-fly ash possessed the most excellent friction reduction and anti-wear performances than other lubricating oils. (24)

3. Summary

- To improve strength of low carbon steel, heat treatment followed by multi-cyclic equal channel pressing is useful but in high carbon steel only heat treatment process can improve strength as effect of multi-cyclic equal channel pressing is negligible.
- To improve hardness of steel, it was coated with Nickel sulfamate bath and Nickel watts bath. Hardness increases in case of Uncoated Specimen, Nickel watts bath and Nickel sulfamate bath respectively.
- Plasma nitriding is useful to reduce friction and wear at elevated temperatures in tool steel. TiAlN coating on UHSS has improved friction behavior at elevated temperatures while MoS2-Ti improve friction behavior at moderate temperatures.
- In low carbon steel, friction coefficient of specimen can be decreased by processes Carburizing-Tempering, Nitride-Carburizing-tempering and carburizing-nitriding. Wear resistance is more in case of carburizing-tempering than carburizing-nitriding than nitride-carburizing-tempering.

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