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ABRASIVE WEAR OF INTERNAL COMBUSTION ENGINES

El-Sherbiny M. G.* and Ali W. Y.**

***Faculty of Engineering, Cairo University, P. N. 12316, Giza, EGYPT.**
****Faculty of Engineering, Taif University, Al -Taif, K. S. A.**

ABSTRACT
There is an increasing demand of studying abrasive wear of internal combustion engines caused by sand particles to meet the severe working conditions in Arab countries represented in the high ambient dust concentrations. Sand covers more than 95 % of the land and the warm desert regions are characterized by sudden fluctuations in wind speed and temperature seasonally. Airborne contaminant levels are particularly high and the maximum concentration measured was approximately 1.0 milligram per cubic meter. During severe storm conditions dust concentrations of the order of 100 to 500 times higher may be encountered.

In the present work, wear particles, retained by oil filter of an internal combustion engine working in El-Minia Governorate, were examined by optical microscope to reveal details of size, shape and quantity of particles. It was detected the generation of large severe wear particles that signal the imminent failure of wearing surface. Particles in the form of loops, spirals, and bent wires were generated, where increase in the number and size of these particles showed that an abrasive wear mechanism is progressing rapidly. Sand particles of different size in relatively high concentration were detected. Based on this observation, it can be concluded that the prevailing mode of wear was abrasion.

Based on the results of the present work, it is necessary to develop the oil, air and fuel filters. Besides, proper selection of oil additives will improve the performance of the engine through decreasing both friction and wear. The recommended type of oil additives is that of polar molecules that can adhere to the sand particles and sliding surfaces to decrease abrasion action of sand particles.

KEYWORDS
Sand and wear particles, oil lubrication, internal combustion engines, antiwear additives, oil filters.

INTRODUCTION
The demand of studying abrasive wear is increasing to meet the high ambient dust concentrations experienced. The operating environment in Middle East is particularly severe in terms of the high ambient dust concentrations. Sand covers more than 90% of the lands and

the warm desert regions are characterized by sudden fluctuations in wind speed and temperature seasonally. Airborne contaminant levels are particularly high and the maximum concentration measured was approximately 1.0 milligram per cubic meter. During severe dust storm conditions dust concentrations of the order of 100 to 500 times higher may be encountered. Abrasive wear is a form of wear which is frequently encountered in industry. Engineers used to divide the abrasive wear into two types. One is two-body abrasion, the other is three-body abrasion. Compared to two-body abrasion, three-body abrasion is much more common. Failures of crusher walls, ball mill liners and balls, even the hard disk in computers are attributed to three-body abrasion.

In desert areas, abrasive particles entering the machines cause serious wear of the sliding components. To improve the wear resistance of the machine parts, the Al_2O_3, TiO_2, Si_3N_4, diamond nano-particle strengthened nickel-based brush plating composite coatings were prepared by co-deposition of nano-particles with Ni metal–matrix, [1]. The main wear mechanisms of the coatings under abrasive contaminant lubrication are plastic deformation, micro-cutting, and scuffing wear. The superior wear resistance of the composite coating is attributed to its fine compact microstructures and high micro-hardness.

It is well known that the failure of engines is mainly caused by seizure or wear of machine elements. The diagnosis of the operating conditions and the length of life of tribo-components without stopping a system can improve the safety and reliability of the engine. The diagnosis is carried out by the physical inspection (Ferrographic oil analysis) and the chemical examination of wear debris (spectrometric oil analysis) to monitor the lubricating condition and to predict failure, [2 – 6]. A diagnostic technique that can estimate quantitatively wear amounts under lubricated condition was developed using developed on-line particle counter, [7]. The wear amounts obtained by the quantitative estimation were fairly similar to the measured values of mass loss of the specimen.

It was found that oil filters contain the most significant wear particles and solid contaminants which characterize the mode of engine wear. Besides, they remove and store metallic, non metallic and polymeric particles generated from the rubbing surfaces. The size and morphology of wear particles obtained from oil filters, that are much bigger than those deposited by Ferrography, described the past history of wear and signaled the early failure of the sliding surfaces through following the striation marks caused by abrasion, [8, 9]. The temper colours of wear particle surface, which can give specific information about the temperature of the sliding surface from which wear particle was removed, were much pronounced for oil filter.

Abrasive wear is the removal of surface material through the cutting action of relatively harder particles against a relatively softer surface, [10]. Grinding, sanding, and polishing processes are all examples of intentional abrasive wear. Abrasive wear occurs in lubricated systems primarily through contamination of the oil by sand particles. Wear particles resulting from abrasive wear of steel are work hardened and themselves act as abrasives. The size of wear particles produced by abrasion typically increases with the severity of the wear, [11]. The solution to any abrasive wear problem is to first change the oil and filter, and then identify and eliminate the source of the abrasive particles. Note that abrasive wear may continue after an oil change for a short period of time if abrasive particles have been embedded in soft bearing materials.

Three body abrasive wear can be classified into two types: with rolling particle motion and with grooving particle motion. Wear modes in the micro-scale abrasion test can be changed from ‘three-body’ abrasion (with rolling particle motion) to ‘two-body’ abrasion (with grooving particle motion) by changing the load [12], the volume fraction of abrasive in the slurry [13], the abrasive particles, the materials of ball and specimen, and the ball surface condition [14]. A critical condition was proposed for the transition from ‘three-body’ to ‘two-body’ abrasion.

Three-body abrasion is, however, much more complicated than two-body abrasion. It has been concluded, [15 - 19], that the movement patterns for abrasive particles can be exactly defined as sliding and rolling. When abrasive particles slide, the wear pattern is the same to two-body abrasion. When abrasive particles roll, the wear will predominantly depend upon plastic deformation behavior, that is, low-cycle fatigue mechanism of material. Because there are a lot of particles to roll in three-body abrasion, plastic deformation wear will be much more important in three-body abrasion than that in two-body abrasion.

The random characteristic of a three-body process should be very important for predicting the wear rate of material. The particles contours characteristic in one batch abrasives, the embedded particles sizes and the topography of worn surface are the main variables. Monte Carlo simulation will provide a good investigating method for predicting the wear rate, [20 – 21].

The wear and friction of cylindrical contacts caused by lubricant abrasive contaminants is reported, [22]. Different particle size abrasive as well as the abrasive used for testing of automotive oil filters and air cleaners were added to the lubricant. The experiments show that three body abrasive wear is mainly dependent on the embed ability of abrasive in the rubbing surfaces. The embedment of the abrasive particles is classified into weak, partial and complete. The effect of both antiwear and dispersant lubricant additives on wear and friction caused by lubricant abrasive contaminants was tested, [23]. Dispersant additive has been added to the base oil with/without antiwear additives such as ZDTP and CMOC. It can be concluded that, for base oil containing only dispersant additive, wear and friction slightly increased with increasing the concentration of dispersant additive. While for base oil containing both of dispersant and antiwear additives, wear decreased significantly with increasing dispersant additive concentration.

Experiments have been carried out to test the friction and wear of piston ring specimen and cylinder liner, constructed in a test model. Abrasive contaminants of different particle sizes were added to the oil at controlled concentrations. On the basis of the obtained results, [24], the effect of abrasive particle size on wear and friction was described and the required filter fineness was recommended.

A magnetic particle separator has been installed to a filtration system to collect ferrous contaminants introduced to the unit from machining and assembly processes, [25]. The microscopic inspection of the retained contaminants confirmed the presence of large ferrous particles of different shapes produced from the machining processes of the unit components. This study recommends the importance of initial cleaning of machine elements before assembly.

It was observed that the effect of the abrasive contaminants can be reduced by the addition of polymeric powders, [26]. The addition of polymeric powder with a particle size relatively greater than that of the contaminant can be considered as a useful method of eliminating the cutting action of the three-body abrasive mechanism introduced by the presence of the hard contaminant particles.

Wear of the tested polymers decreased with increase of sand particle size down to minimum because of the sand embedment in the polymeric surface, [27]. Further increase in sand particle size increased wear due to the removal of sand from the polymeric surface. Sliding of polymer against polymer decreased both friction coefficient and voltage generated, while wear increased due to the decrease of sand embedment in the polymeric surface.

In the present work, wear particles retained by oil filter of automotive engine were examined by optical microscope to have information about wear mechanism prevailed during the tests. Besides, the effect of different antiwear additives on friction and wear in the presence of lubricant abrasive contaminants was investigated.

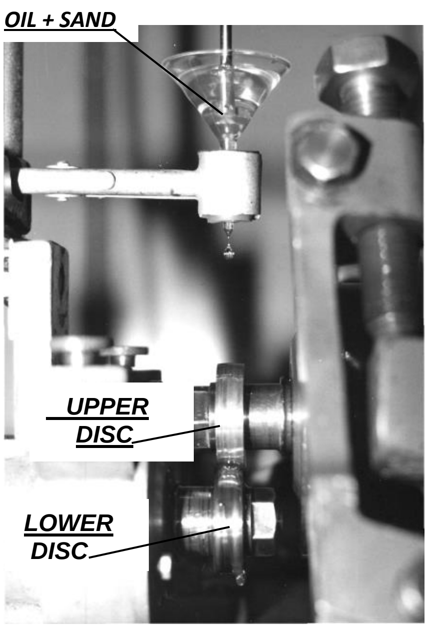
EXPERIMENTAL

Wear particles were examined using optical microscope. The examination of wear particles, retained by the oil filter disassembled from the two tested engines, was carried out to determine the wear mechanisms, which occurred during the operation of the two engines. The oil filter housing was opened. A square piece, 20 × 20 mm, of the pleated papers was cut and ultrasonically scrubbed in 50 ml of normal heptane to redisperse the particles for 30 minutes. Then the wash was filtered by 0.4 μm membrane. The material deposited on the membrane was considered to be the wear and solid contaminant as well as oxidation products. The membrane was washed by 50 ml of benzol to dissolve the oxidation products. Examination of the membrane by the bichromatic microscope showed the morphology of the wear particles that formed as a result of engine operation. The piston rings and cylinder liners as well as bearings were disassembled from the engine and their surfaces were examined by optical microscope.

Series of experiments were carried out to test the effect of adding antiwear additives into the lubricating oil. These additives were heteropolar organic compound as copper base additive {Chelate Metal Organic Compound (CMOC)} in form of copper quinolinolate Cu C_{18}

H_{12} O_2 N_2, polytetrafluoroethylene (PTFE) base additive and Molybdenum disulphide (MoS_2) base additive were used with 4.0 wt. % concentration.

Experiments were carried out by Amsler testing machine, Fig. 1. The test specimens, in form of discs, were gray cast iron (3 % C, 1.4 % Si and 0.8 % Mn, DIN 1691) and plain carbon steel (0.35 % C, DIN 1611). The surface roughness of the test specimens was 0.7 µm, R_a. The dimensions of the test specimens are shown in Fig. 2. The test specimens were held in the upper and lower shafts which were rotating by 193 and 173 r/min that equals to linear velocity of 0.8 m/s. Cast iron disc was held in the upper shaft, while aluminium alloy, bronze and steel disc were assembled to the rotating shaft. Friction coefficient was determined by measuring the friction torque using a pendulum device, which is a part of Amsler machine. Wear was measured by the weight loss of the cast iron disc measured by electronic balance of ± 0.1 mg accuracy.



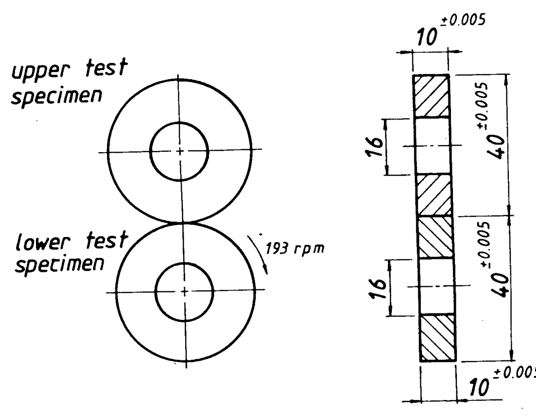


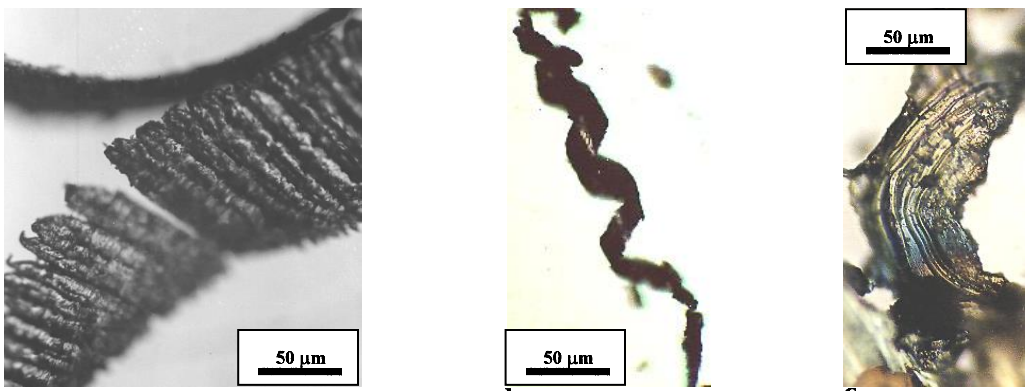
Fig. 1 Arrangement of the test rig. **Fig. 2 Test specimens dimensions.**

Paraffin oil was used as a lubricant. The abrasive contaminant was air cleaner fine test dust (ACCTD) of particle size ranging from 0 – 200 µm added to the oil at 1.0 % concentration. Tests were carried out at 200 N applied load for 60 minutes. The worn surfaces of the test specimens were examined microscopically. The base oil has a viscosity of 0.40 Pa.s at 25 °C and was by gravity fed at room temperature of 25°C.

RESULTS AND DISCUSSION

Examination of the membrane by the bichromatic microscope reveals details of size, shape and quantity of particles. The generation of large abrasive wear particles signals the accelerated wear rate of sliding surface. Abrasive wear generates particles in the form of loops, spirals, and bent chips, Fig. 3. Increase in the number and size of these particles shows that an abrasive wear mechanism is rapidly progressing.

Cutting wear particles are generated as a result of one surface penetrating another. There are two ways of generating this effect. The first when a relatively hard component of hard sharp edge penetrates a softer surface, Fig. 4, where the propagation of cutting process is shown from right to left. Particles generated this way are generally coarse and large, averaging 2 to 5 microns wide and 25 microns to 100 microns long. The second when hard abrasive particles in the lubrication system, either as contaminants such as sand or wear debris from another part of the system, may become embedded in a soft wear surface (two body abrasion) such as a lead/tin alloy bearing. The abrasive particles protrude from the soft surface and penetrate the opposing wear surface. The maximum size of cutting wear particles generated in this way is proportional to the size of the abrasive particles in the lubricant. Very fine wire-like particles can be generated with thickness as low as 25 microns. Occasionally small particles, about 5 microns long by 25 microns thick, may be generated due to the presence of hard inclusions in one of the wearing surfaces.



a. b. c.

Fig. 3 Wear particles; a. Segmented chip, b. Continuous chip, c. Continuous chip with built up edge.

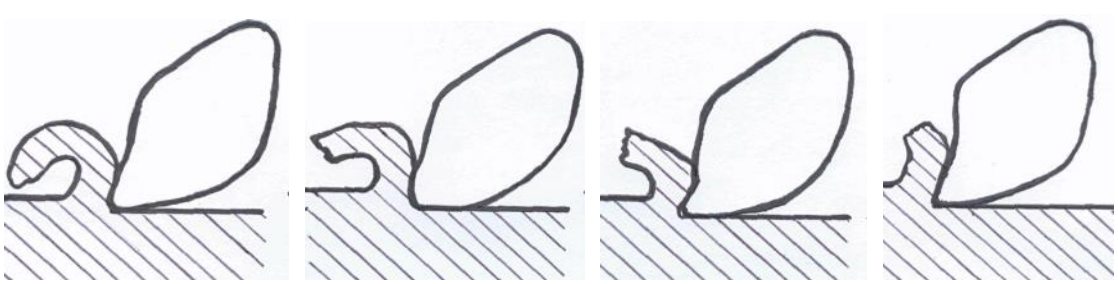


Fig. 4 Propagation of the cutting process generated by abrasive particles.

Machining operations produce chips of three basic types, discontinuous (segmented), continuous, and continuous with built-up edge, Fig. 5. Conditions that favor the production of discontinuous chip are Brittle surface materials, large chip thickness and low sliding speed. Continuous chip is produced from ductile work material, small chip thickness (relatively fine feeds), sharp cutting hard edge, large rake angle on cutting edge, high cutting speeds, cutting edge and surface kept cool by enough lubricant film to give minimum resistance to chip or the cutting edge materials have low coefficient of friction such as alloys containing lead, phosphor, and sulphur. Continuous chip with built-up edge is produced from low and high carbon alloyed steels, low cutting speed in the absence of cutting fluids.

Abrasive particles contaminated in the oil and fuel were collected by the oil and fuel filters and examined by microscope, Fig. 6. The particle size approached 200 μm. Considering the values of clearance between sliding surface inside the engines can signal the severity of abrasive wear.

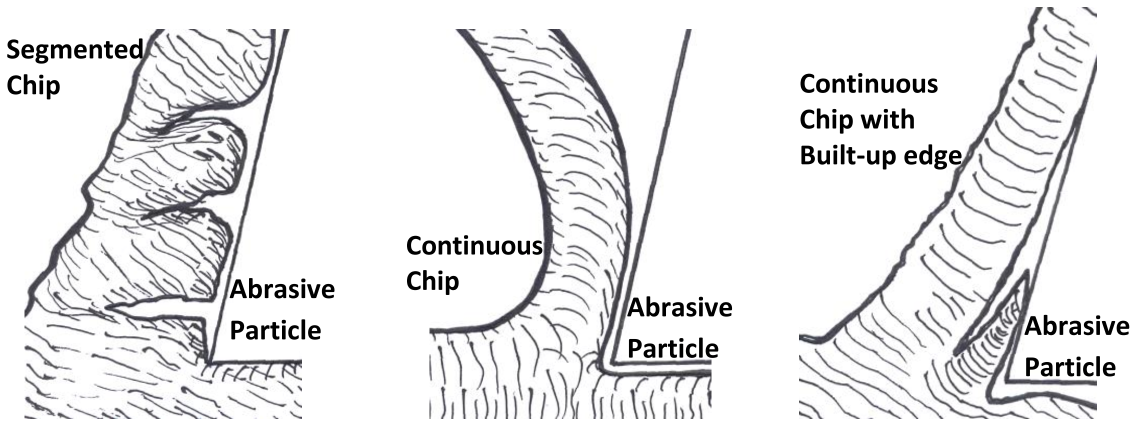


Fig. 5 Types of chips generated from the interaction of abrasive particles.

Examination of the worn surface of piston ring test specimen using an optical microscope is shown in Fig. 7. The figure illustrates a wear mode in which breakdown of the boundary lubricant film occurs, where the shear mixed layer becomes unstable and severe plastic flow of the surface results. Also, the generation of black oxides representing a more severe form of oxidative wear is shown. The abrading action of abrasive contaminants in the test specimen surface has led to a catastrophic wear mode which is indicative of surface failure. The embedment of abrasive particle in the surface of the cylinder liner is shown in Fig. 8. The cylinder liner test specimens also suffered from abrasive particle embedment. A big abrasive particle of 30 μm size is embedded completely in the bronze bearing surface, Fig. 9. The bronze flows in the direction of motion of the rotating steel shaft and covers the abrasive particle partially. The complete embedment does not permit the particle to roll. When the layer of bronze that covers the particle is worn, the abrasive particle begins to cut the surface of the steel shaft.

The results of the experiments carried out to investigate the effect of the tested additive on the friction and wear of test specimens lubricated by base oil contaminated by sand particles are illustrated in Figs. 10 and 11. Friction coefficient displayed by using base oil (SAE 30), and oil dispersed by PTFE, MoS_2 and CMOC is shown in Fig. 10. Generally, friction coefficient decreased with increasing running time due to the decrease of the surface roughness of the sliding surfaces. Further decrease in friction was observed for oil dispersed by the tested additives. CMOC additive displayed the minimum values of friction coefficient followed by PTFE and MoS_2. The effect of the additives on wear is shown in Fig. 11. CMOC additives exhibited the lowest wear values followed by PTFE and MoS_2. It can be noticed that the values of both friction and wear were significantly affected by the tested additives.

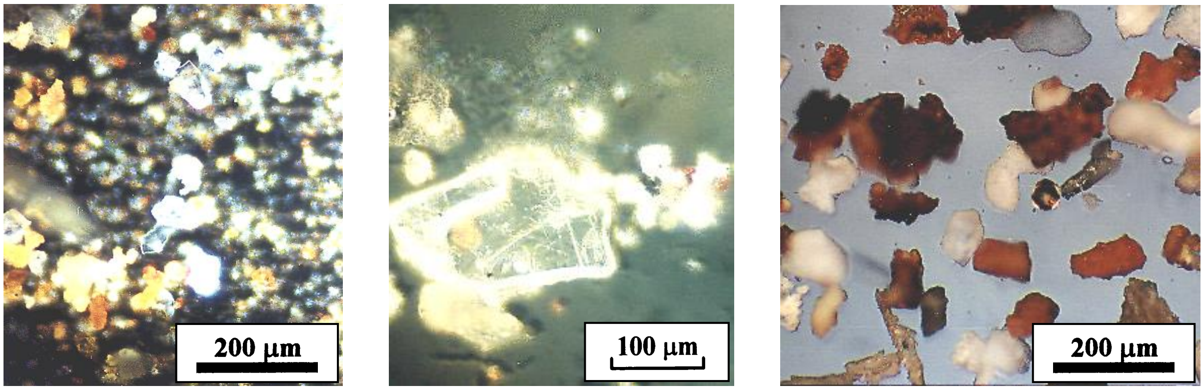


Fig. 6 Abrasive particles contaminated in the oil.

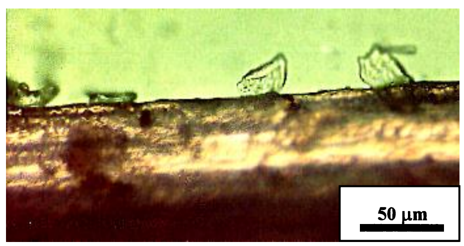


Fig. 7 Abrasive particles embedded in the surface of piston rings.

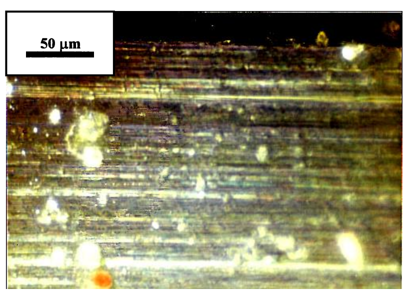


Fig. 8 Abrasive particles embedded in the surface of cylinder liners.

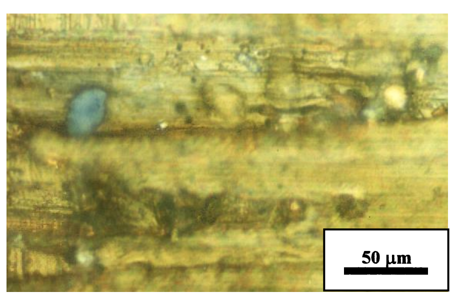


Fig. 9 Abrasive particle embedded in the surface of the bearing.

Based on the experimental observations, it can be noticed that the addition of CMOC performed significant reduction in friction and wear. The mechanism of action was due to the ability of polar particles to build a protective layer on the rubbing surfaces and prevent metal to metal contact. Besides, the particles of the additives smaller in size than 1.0 µm adhered to the surface of the wear and solid contaminants and made them less abrasive, Fig. 12. Besides, its mechanism of action depends on the selective migration where selective diffusion of tin, lead and zinc ions into solution from copper alloy produces a soft thin surface layer stabilized by electrical interaction between sub-layers and the surface. Copper does not form carbides and also being soft and good heat conductor, it should not produce high rubbing temperatures which normally lead to scuffing. In addition to that, the CMOC particles can interact with each other, due to the direct effect of the electric static force, and form multilayer film adhering to the sliding surface effectively. Triboelectrification induces an interfacial polarization on the particles owing to a mismatch of the dielectric constant among the particles, and the polarization thus induced on the particles plays a role to form a chainlike structure along the electric field, leading to the increase in the viscosity of the suspension.

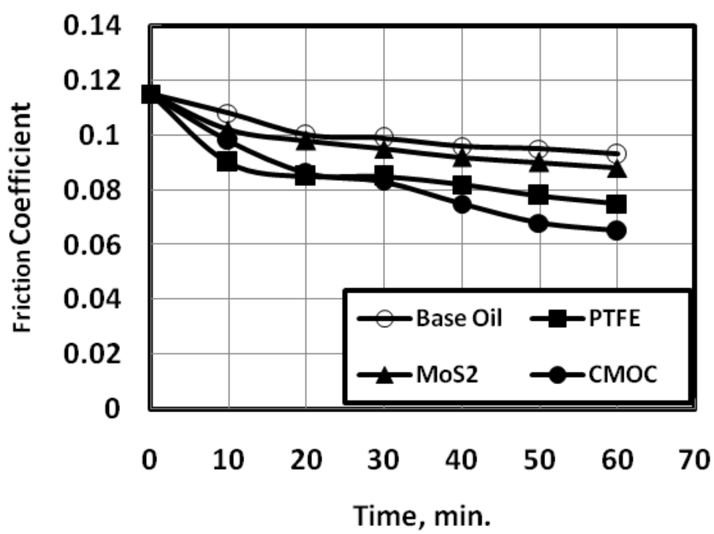


Fig. 10 Effect of the tested additives on the friction coefficient.

The good lubricating properties observed for PTFE base additive can be from its ability to form a monomolecular layer on the friction surfaces. The very low intermolecular forces of PTFE then allow this surface film to slide over the friction surface with a minimum of interaction. The good lubricating properties observed for polytetrafluoroethylene (PTFE) base additive can be from its ability to form a monomolecular layer on the friction surfaces, Fig. 13. The very low intermolecular forces of PTFE then allow this surface film to slide over the friction surface with a minimum of interaction and hence a minimum of wear. Its mechanism of action was limited in condition of abrasive sand particles contaminating lubricating oil.

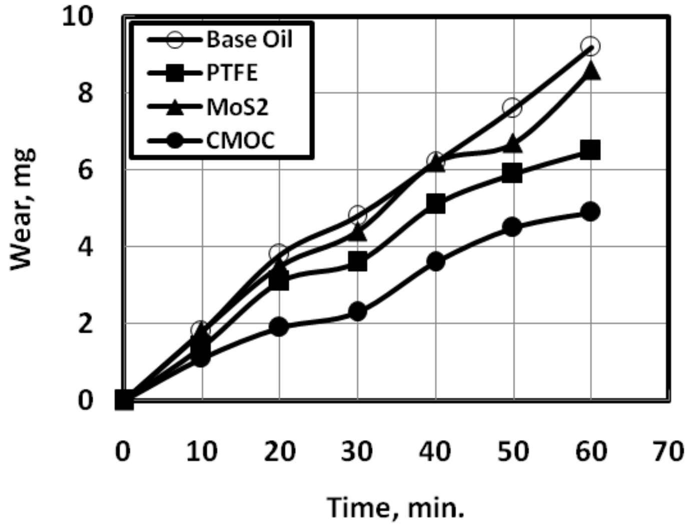


Fig. 11 Effect of the tested additives on wear.

MoS_2 base additive is a good lubricant where under the influence of the moving surfaces, aggregates are disrupted and the solid MoS_2 fills in the pits and valleys, there by reducing roughness, increasing the true area of contact and providing a reservoir of lubricant. The drawback of MoS_2, as an antiwear additive dispersed in oil, is in its insolubility which causes flocculation and settling during use and he adherence of MoS_2 into the surfaces of sand particles is weak, Fig. 13. Besides, MoS_2 additives cannot withstand the severe abrasion caused by sand particles.

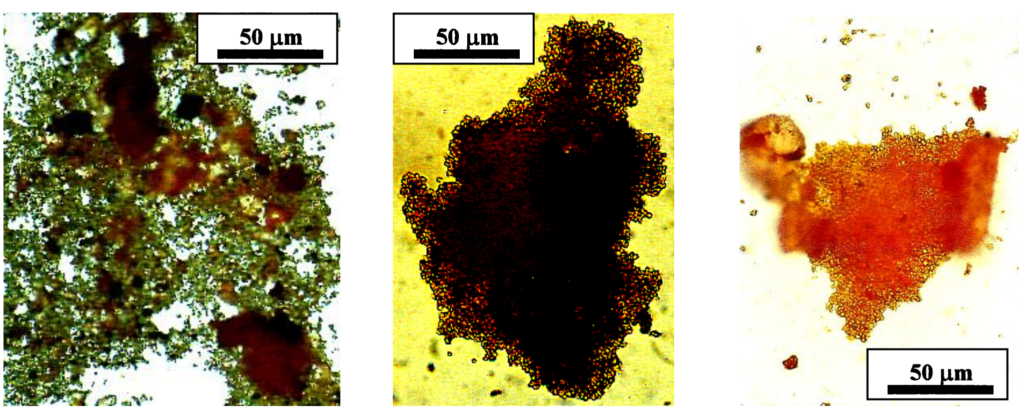


Fig**. 12 Adherence of the Particles of CMOC additive into the surface of the abrasive particles.**

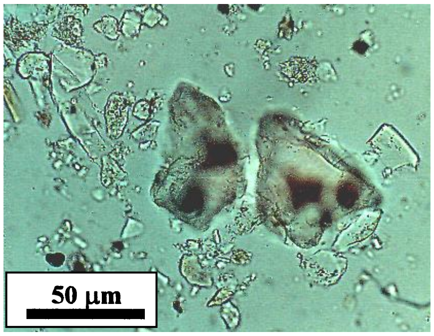


Fig. 13 Sand and PTFE particle.

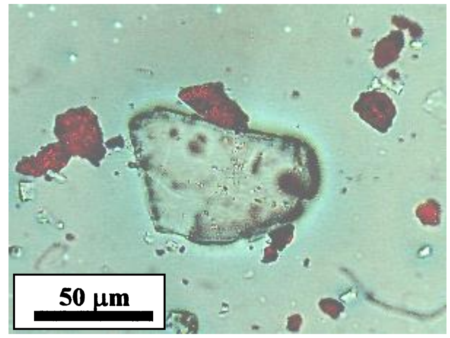


Fig. 14 Sand and MoS_2 particles.

CONCLUSIONS

Examination of solid contaminants retained by the oil filter provides specific information to identify the wear and solid particles contaminated in lubricating oils used in automotive engines. This information confirmed that the dominant wear type was abrasion. The lubricating oil was severely contaminated by sand particles of different sizes and concentrations as well as foreign particles from fresh oil and wear debris. Presence of such particles accelerates abrasive as well as fatigue wear. Besides, detection of abrasive wear particles confirmed the early failure as well as accelerated wear of the sliding surfaces.

It can be recommended to filter the lubricating oil by a separate filtration unit at regular intervals. The proper oil additives for reducing abrasive wear are that of polar molecules that can adhere to the sand particles and sliding surfaces to decrease abrasion action of sand particles.

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