EGTRIB Journal
JOURNAL OF
THE EGYPTIAN SOCIETY OF TRIBOLOGY
VOLUME 8, NO. 3, JULY 2011, 15 - 26

INSPECTION OF WEAR PARTICLES RETAINED BY THE OIL FILTERS OF AUTOMOTIVE ENGINES

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ABSTRACT
There is an increasing demand of monitoring wear of automotive engines to control the severe working conditions in Arab countries represented in the high ambient dust concentrations. In the present work, wear particles, contaminating the lubricating oils of automotive engines running in Kingdom of Saudi Arabia, were examined by optical microscope to reveal details of their size, shape and quantity of particles. The visual inspection of those particles by microscope described the wear mechanism, detected the transfer from one wear mechanism to the other and identified the abnormality of wear. The photomicrographs of wear particles provided specific information about the severity of wear and the working conditions. The available information can help in the study of tribological problems such as friction, wear and lubrication as well as developing filtration technology and testing the sliding surfaces inside automotive engines. The generation of large severe wear particles that signal the imminent failure of wearing surface was detected. Those particles were in the form of fatigue and abrasive types, where their increase in the number and size showed that fatigue and abrasive wear mechanisms were progressing rapidly.

Based on the results of the present work, some proposals and recommendations should be considered 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.

KEYWORDS
Wear particles, automotive engines, oil filters.

INTRODUCTION

The global pollution of environment is generally caused by the combustion products of internal combustion engines. For this purpose, some of the researches have been focused on fuel additives to reduce harmful emissions, while the others are focusing on reducing wear of the moving surfaces inside automotive engines. Fuel properties are developed by

using some additives to improve combustion efficiency and to decrease pollutant emissions, [1 - 6].

The demand of studying wear of automotive engines 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. 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, [7]. 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, [8 – 12]. A diagnostic technique that can estimate quantitatively wear amounts under lubricated condition was developed using developed on-line particle counter, [13]. 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, [14, 15]. 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, [16]. 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.

Inspection of wear particles, retained by oil filter of automotive engines working in Egypt, were examined by optical microscope to reveal details of the size, shape and concentration, [17]. The generation of large severe wear particles that signal the imminent failure of wearing surface was detected. Worn particles in the form of loops, spirals, and bent wires were generated, where the increase in the number and size of these particles indicated that an abrasive wear mechanism was 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.

In the present work, wear particles retained by oil filters of automotive engines were examined by optical microscope to have information about wear mechanism prevailed in the region in which the automotive engine were working.

EXPERIMENTAL

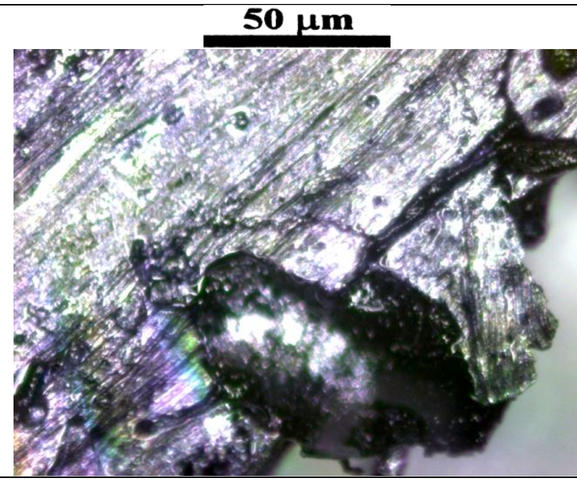
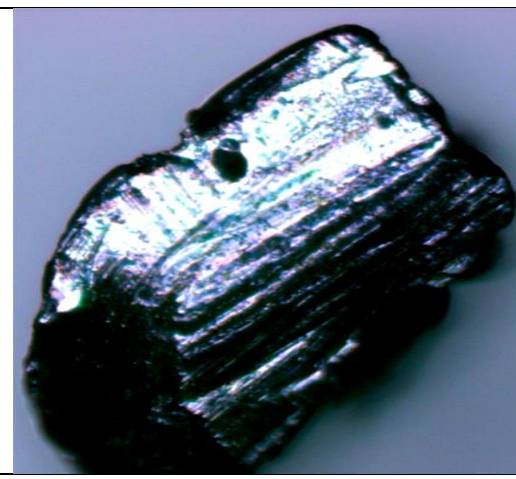
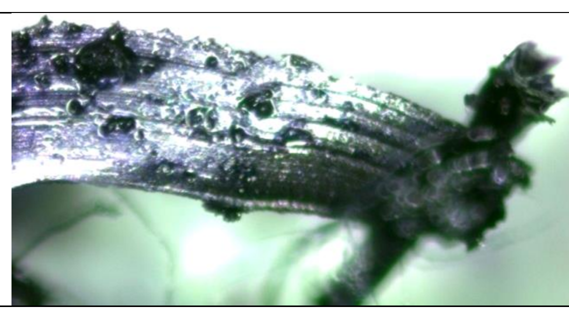
Oil samples were collected from five different automotive engines running in Taif City in Saudi Arabia as well as their oil filters. The filter element was removed from the filter housing. A square piece, 20 × 20 mm, of the pleated papers was cut and ultrasonically scrubbed in 50 ml of normal heptane 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 revealed the generation of wear particles. The ferrous particles were separated from the diluted oils or filtrates by using a magnetic rod covered by a plastic sheet to facilitate the removal of the attracted ferrous particles.

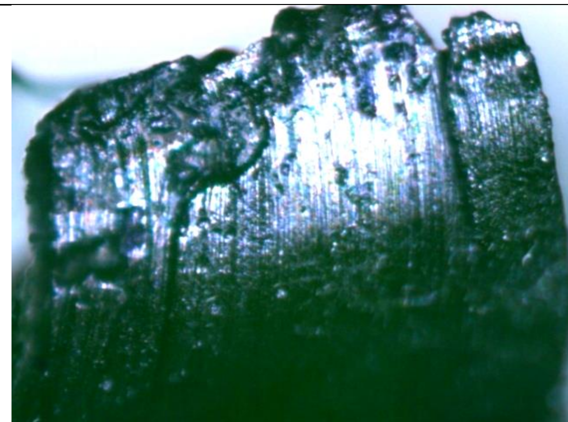
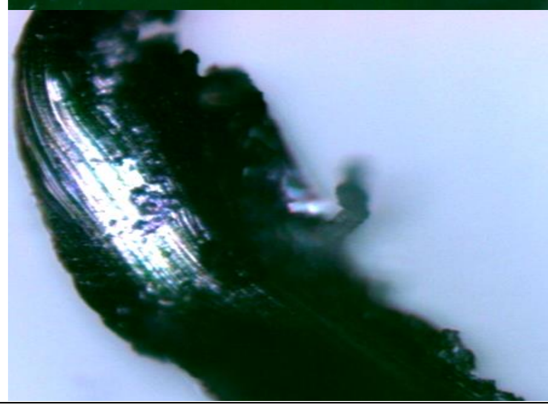
RESULTS AND DISCUSSION

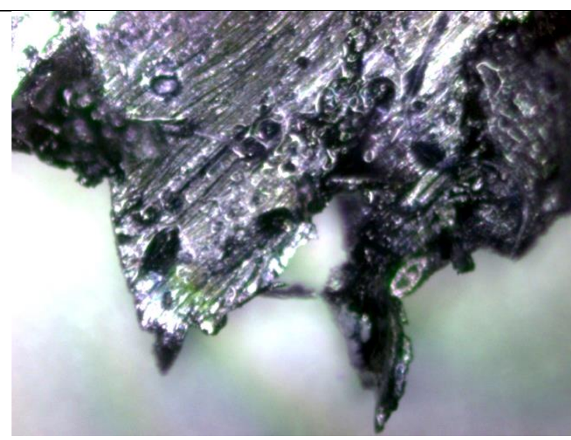
Materials of wear debris consist of ferrous alloys (cast iron and steel) removed from cylinder liners, crank shaft, timing gears, cam shaft and piston rings. Copper alloys are produced from top end bushes, crank and main bearings, while aluminium alloys are generated from wear of piston skirts, camshaft bearings and timing gear bushes.

Inspection of wear particles retained by the oil filter showed complete surface failure detected by very big wear particles. Wear particles were of surface striation indicating severe sliding. This would be occurred due to the lack of lubrication. Examples of the different types of wear particles collected from the tested automotive engines are illustrated in the Table 1. It can be observed that examination of the oil filters disassembled from the tested engine revealed the presence of very large flaky wear particles removed from the sliding surfaces of pistons, piston rings, cylinder liners, sliding bearings and crankshafts.

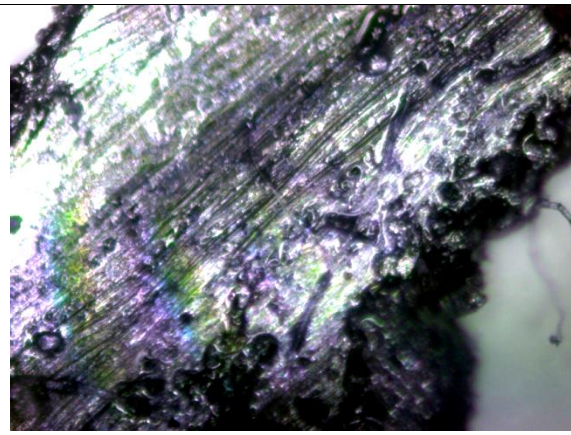
Table 1. Wear particles retained by the oil filters disassembled from the tested automotive engines.

Severe sliding wear begins when the stresses on the wear surface become excessive from high loads or speeds. The shear mixed layer becomes unstable, and large particles break away, causing an increase in the wear rate. If the stresses applied to the surface are increased even more, a second transition point is reached at which the complete surface breaks down and a catastrophic wear rate continues.	
Fatigue particles have a smooth surface and are frequently irregularly shaped. The particles may have a ratio of major dimension to thickness between 4:1 and 10:1. The chunkier particles result from tensile stresses on the contact surface, causing the fatigue cracks to propagate deeper into the contact surface prior to spalling. A high ratio of large particles to small ones is also found as in rolling bearing fatigue.	
The abrading action of abrasive contaminants has led to a catastrophic wear mode which is indicative of surface failure. A big abrasive particle of 100 µm long and 40 µm wide is shown. The size of particles can indicate the size of sand particles contaminated in the oil.	

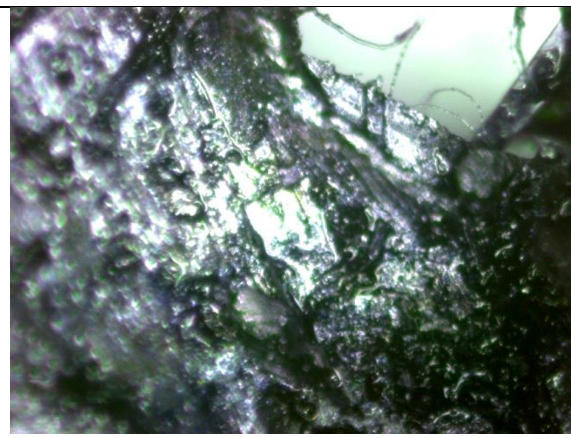
Cutting wear particles are generated as a result of one surface penetrating another. The second when hard abrasive particles in the lubrication system, either as contaminants such as sand or wear debris, may become embedded in a soft worn surface (two body abrasion) such as a lead/tin alloy bearing. The abrasive particles protrude from the soft surface and penetrate the opposing worn surface. The maximum size of cutting wear particles generated is proportional to the size of the abrasive particles in the lubricant. The size of abrasive particles contaminated in the oil approached 200 µm. Black oxides are dark gray to black, and they resemble pebbles. The oxide in this case is Fe_3O_4. Black oxides indicate a more severe condition than do red oxide particles. More iron is being consumed in the oxidation process, as a result of inadequate lubrication.	 

Relatively big fatigue particles are shown. These photomicrographs reveal the irregular shape of particles resulting from surface fatigue. The particle is typical chunky type. Severe fatigue wear particles are 150 µm or greater in size. Some of these particles have surface striations as a result of severe sliding. They frequently have straight edges. As the wear becomes more severe within this wear mode, the striations and straight edges on particles become more prominent.	

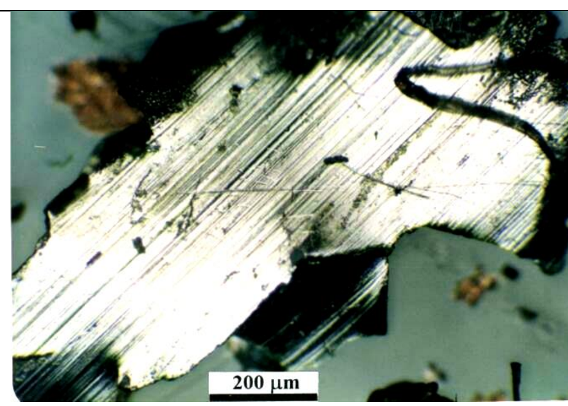
Large free metal particles resulting from complete surface breakdown is shown. The larger particles cannot be photographed at this high magnification. The used method of filter inspection is proposed to retain the large particles. Efficient lubrication of the moving surfaces helps to prevent the formation of those particles. Because of the thermal nature of scuffing, quantities of oxides are usually present, and some of the particles may show evidence of partial oxidation, where the degree of oxidation depends on the lubricant and the severity of scuffing.



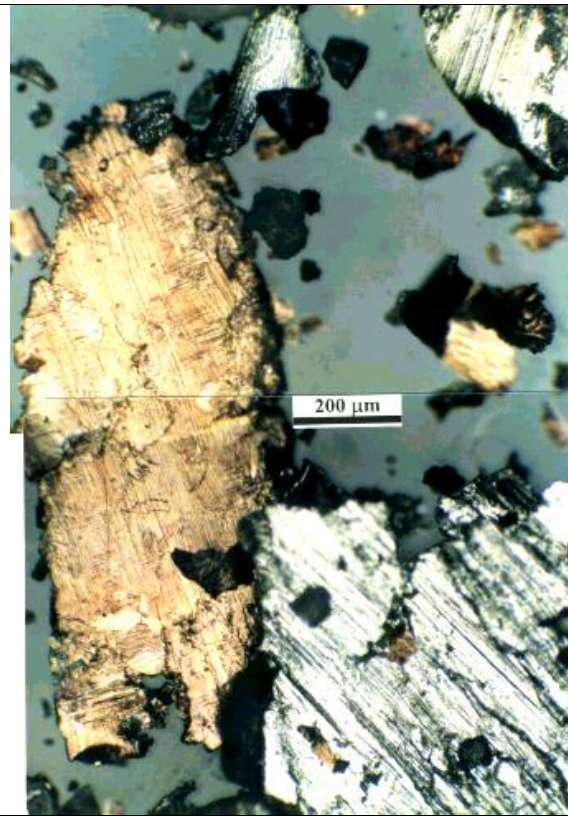
The major causes of fatigue wear are scuffing or scoring, severe sliding wear, overload wear, and wear from abrasive contaminants. The fatigue particles were suspected to originate from the sliding surface by the pitting wear mode, due to their generally smooth surface and presence of straight edges. Scuffing of sliding surfaces is caused by too high a load or too high a speed. Excessive heat breaks down the lubricant film and causes adhesion of the counterface.



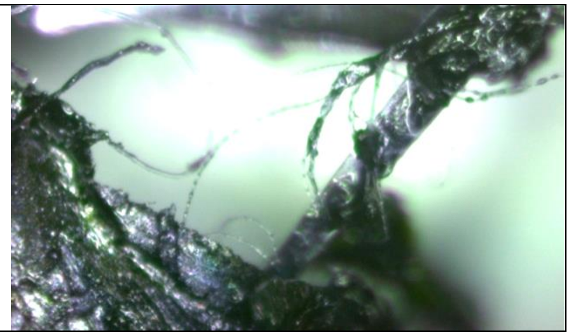
Free metal particles up to 1 mm indicates the catastrophic failure of the moving surfaces as shown. The external boundaries of the particle were oxidized shown as dark areas. These particles resemble dark oxide sliding wear, except that they contain a core of free metal. These particles are caused by heat and by lubricant starvation. They indicate more severe wear than red oxide sliding.

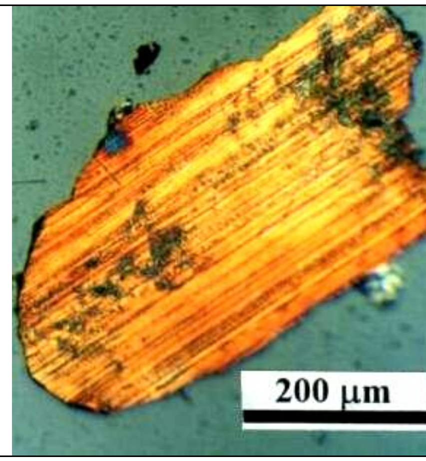


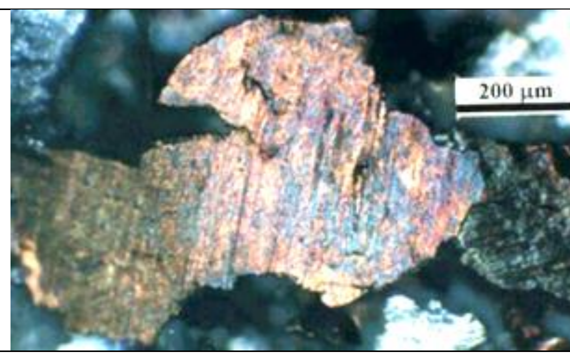
When materials of different hardness are in continuous contact, the softer surface tends to become grooved while the harder surface has large particles of the soft material adhering to it. This behaviour characterizes the wear mechanism in which breakdown of the boundary lubricant film occurs, where the shear mixed layer becomes unstable and localized adhesion and severe plastic flow of the surfaces results causing the formation of the relatively large particles. These particles are formed in conditions of inadequate lubrication and are in effect of oxidation of severe sliding wear particles, with the oxide being Fe_2O_3. Particles of this type that are thick and rounded (with a thickness ratio similar to that of chunks) may originate from fretting mechanisms.



Free metal wear particles having dimensions ranging up to 1 mm is shown. This particle represents the catastrophic sliding wear mode, which is indicative of failure of the surfaces. Excessive surface shear stresses cause the complete breakdown of one or both surfaces and the generation of free metal wear particles having dimensions up to 1 mm. Once initiated, scuffing usually affects the contact area, resulting in a considerable volume of wear debris. All the particles tend to have a rough surface and a jagged circumference. Some of the large particles have striations on either surface, indicating severe sliding contact.

Polymeric fibres are shown. The source of these fibres is the filtering material. The increased number of the fibres indicates that the filtering materials suffers from failure.	

Large free metal particles resulting from complete surface breakdown is shown. Recirculation of the larger wear particles often generates grooves in the metal surfaces depending on the running conditions. The depth of the grooves is deeper and wear rates are higher for soft materials than hard ones.	

Severe wear particle of alloyed steel is shown. Traces like striations of blue and orange colour are seen on the surface. The particle is flat with rounded edges where partial plastic flow has taken place. Plenty of blue temper colour is shown as a result of the excessive heat and/or lubricant starvation during particle generation.	

The relationship between sliding wear particles and the generated surfaces is classified in six regimes of wear. Each regime produces wear particles with characteristics in morphology and composition that aid in monitoring the diagnosis. The first regime contains free metal particles usually less than 8 µm that vary between polished and very rough. One surface can be polished, while the opposing surface is affected. The second regime contains free metal particles usually less than 15 µm which are stable, smooth, shear, mixed layer with a few grooves. Free metal particles usually less than 150 µm ploughed, with evidence of plastic flow and surface cracking are representing the third regime. Red oxide particles as clusters or individually up to 150 µm ploughed, with areas of oxides on the surface are classified as fourth regime. Black oxides particles represent

the fifth regime. Free metal particles up to 1 mm which are severely ploughed with gross plastic flow and smearing are considered as catastrophic and representing the sixth regime.

Sand contaminants can enter into the lubricating system during the fuel filling process. This may also occur when there are dust particles present in the fuel itself due to cleaning problems in the station tanks. These dust particles, Fig. 1, are usually the hard mineral type (SiO_2 or silicates), and are quite capable of wearing down the sliding surfaces. It should be pointed out that dust particles have an equiaxial shape that makes it difficult to retain them with filters. Due to the relatively high concentration of sand particles the filtering system is not able to eliminate them. Therefore, these particles pass directly to the lubricating system, thus causing excessive wear rate of the moving surfaces. Assembling mechanical components is a critical point, and unless it is performed carefully, may lead to the generation of metallic particles which exceed the size of 100 µm. These tend to be sliding and cutting ferrous particles.

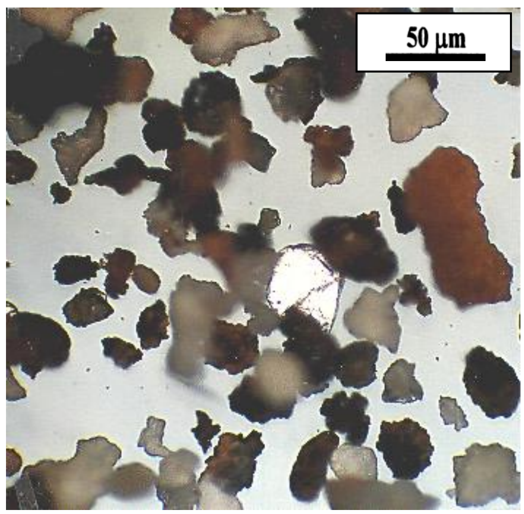
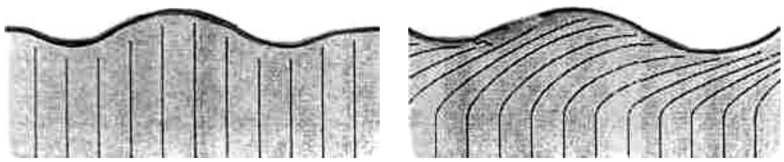


Fig. 1 Sand particles contaminating the lubricating oils of automotive engines.

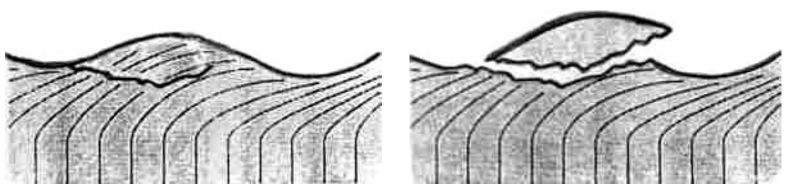
It has been found that wear particles can be formed due to the growth of surface initiated cracks, Fig. 2, when the sliding planes of weakness in the material become distributed parallel to the surface by repeated deformation process, [18]. Also, it was concluded that, [19], fatigue wear during sliding is a result of crack development in the deformed surface layer where the average thickness of the wear particles depends on the thickness of the deformed layer.

Under the action of the applied compressive load, hard asperities on the surface of the relatively harder material penetrate the surface of the softer one, [20]. The stresses at the point of contact are high and cause localized plastic deformation. Relative sliding of the contacting materials is accompanied by repeated extensive deformation of the thin

surface layer of the softer material leading to fatigue of the surface layer and to the formation of wear particles.



a. Undeformed surface. **b. crack initiation.**



c. Crack propagation. **d. Wear particle generation.**

Fig 2. Formation of wear particle due to surface fatigue, [18].

During the contact of the sliding surfaces, asperities of the softer surface are easily deformed and some are fractured by the repeated load. A relatively smooth surface is generated, due to their deformation and/or removal, where the contact is not just asperity to asperity contact, but rather an asperity-plane contact. The surface traction exerted by the harder asperities on the softer surface induces plastic shear deformation, which accumulates with preheated loading. As the subsurface deformation continues, cracks are nucleated below the surface. Once cracks are present, further loading and deformation causes cracks to extend and propagate joining neighbouring ones. The cracks tend to propagate parallel to the surface at a depth controlled by material properties and coefficient of friction. When these cracks finally shear to the surface long and thin wear sheets delaminate, [21]. The thickness of the wear sheet is controlled by the location of subsurface crack growth, which is controlled by the normal and the tangential loads at the surface.

CONCLUSIONS

The mechanism of generation of very large flaky wear particles as a result of the severe wear of internal combustion engines at starved lubricated sliding is explained on the basis of the breakdown of the lubricant film causing the instability of the shear mixed layer accompanied by the localized adhesion and severe plastic flow of the surface. Inspection of oil filters by the proposed method can detect early the start of the failure stage of the sliding surfaces. Consequently, the oil filter should be removed and inspected for every oil change. The conclusion that can be drawn from the wear debris analysis is that the sliding surfaces were wearing out due to surface fatigue (pitting). The presence of fatigue particles of relatively large sizes suggests that an overload condition may have caused the surfaces to fail.

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