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CHARACTERIZATION OF SOLID PARTICLES CONTAMINATING AUTOMOTIVE OILS BY FERROGRAPHIC EXAMINATION

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ABSTRACT
This work aims to examine solid contaminants and wear particles in lubricating oils by Ferrographic oil analysis. Oil samples taken from internal combustion engines, gear boxes, gas turbines and hydraulic machinery have been examined. Ferrography, Is Used to quantify wear and contaminant particles circulating in the oils, and in monitoring the wear process, indicating wear mechanism and detecting wear abnormality. The microscopic examination of particles is discussed.

This investigation guided the study of tribological problems such as friction, wear and lubrication as well as developing filtration technology, oil additives and testing both bearing and mating surface materials.

KEYWORDS
Ferrography, lubricating oil, solid contaminants, wear particles size, wear mechanisms.

INTRODUCTION
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, [1 – 6]. A diagnostic technique that can estimate quantitatively wear 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 by following the striation marks caused by abrasion, [8, 9]. The temper colours of wear particle surface were pronounced for oil filter deposits, which can give specific information about the temperature of the parent sliding surfaces.

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, [10]. The generation of large severe wear particles that signal the imminent failure of wearing surface was frequently detected. 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 also detected. Based on these observations, it can be concluded that the prevailing mode of wear was abrasion.

The wear of internal combustion engines has been studied by Ferrography, [11 - 13], in which engine tests were developed for the determination of the wear particle generation rate and oil filter efficiency. Examples of particle generating surfaces include the cylinder liner, piston rings, main bearings, crankshaft, camshaft and valve guides. The carbon soot contained in the exhaust products can be absorbed into the oil film on the cylinder wall, [14 - 16]. Sand particles can enter into the system through intake air, fresh oil and fuel.

Gear drives were examined by means of Ferrographic analysis to reveal and forecast several faults coming from the performance, mounting and operation, [17]. Gears have many applications in the automobile engine. But two of their major uses are in the gearbox and in the final drive of a vehicle where the operating conditions are severe. The most common failures are due to scuffing, abrasion, pitting, cracking and fracture, [15 - 22]. The mode of gear wear in condition of overloading is classified as severe sliding wear of particle size larger than 20 μm. Some of these particles have surface striations, as a result of sliding, and straight edges.

Ferrographic analysis was carried out for evaluating the safe and economic operation of gas turbines, [23 - 25]. It was concluded that careful monitoring of aero-engines on the test bed can give an indication of service performance. Monitoring of both lubricant washed components and components in the gas stream may be more informative.

In the present work, Ferrographic oil analysis has been applied to examine solid particles contaminated in the oil samples taken from different machinery and the microscopic examination of particles is discussed.

EXPERIMENTAL

Ferrography includes an instrument for the making of Ferrograms and bichromatic optical microscope for visual inspection of solid particles on the Ferrograms. The oil sample is prepared by using three cubic centimeters of the oil and one cc of the fixer. The prepared sample is pumped across the transparent substrate which is mounted at slightly inclined plane and subjected to highly divergent magnetic field so that the magnetic particles deposit along the length of the substrate. A wash cycle is used to remove the residual oil and cause the wear particles to adhere permanently to the Ferrogram, Fig. 1 which is further examined by the Ferroscope, Fig. 2.

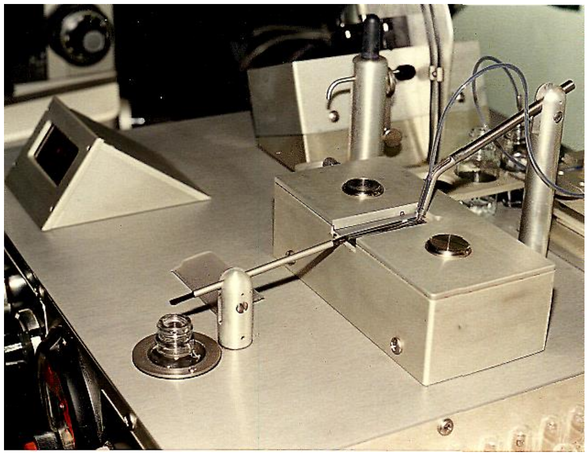
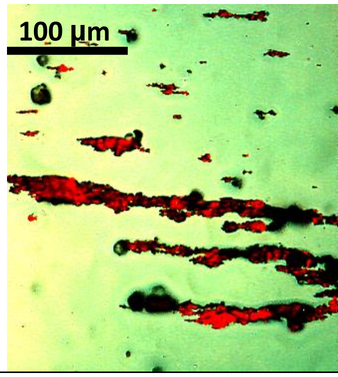


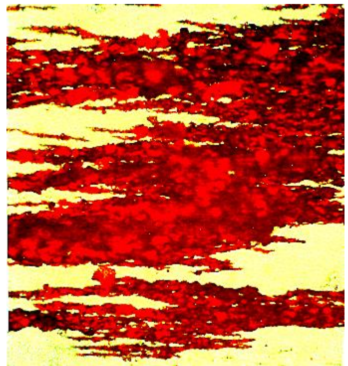
Fig. 1 Ferrograph. **Fig. 2 Ferroscope.**

Examination of the Ferrogram in the bichromatic microscope reveals details of size, shape and quantity of particles. The generation of large severe wear particles signals the early failure of wearing surface. Abrasive wear generates particles in the form of loops, spirals, and bent wires. Increase in the number and size of these particles shows that an abrasive wear mechanism is progressing accordingly. Small platelets are associated with normal rubbing wear. Spheres are generated from rolling surfaces. Fatigue chunks represent material removed as rolling elements spall. Combined rolling and sliding, as in gears, produces scuffing particles and fatigue chunks, [26, 27]. Determination of the composition of particles on the Ferrogram established their origin and the colour aided their identification. After heating the Ferrogram at 330°C for 90 seconds, blue temper colour indicates low alloy steel, light brown colour indicates cast iron and stainless steel is not affected at 330°C but shows mottled bluing at 500°C, [28].

RESULTS AND DISCUSSION

The solid particles contaminated in lubricating oil and described in this work can be classified into normal wear particles, abrasive wear particles, rolling fatigue wear particles, fatigue and scuffing wear particles, polymeric wear particles and sand particles. Normal wear particles are generated from the adhesion of the friction surfaces and running-in wear as a result of removal of grinding ridges, surface asperities and irregularities, Figs. 3 and 4. They are platelets and ranging in size up to 15 μm. Presence of very fine sand particles increases the normal wear rate causing significant reduction in the life time of the moving surface. Normal wear particles are shown in Figs. 3 - 5. The combined action of adhesion between asperities and sliding motion causes severe plastic deformation of the asperities, [29]. Sliding ads shear stress to the normal stresses and consequently increases the probability of plastic flow and fracture of materials in the contact region. Material in the softer asperity deforms to a certain limit then a crack extends across the asperity producing loose wear particle, [30, and 31].





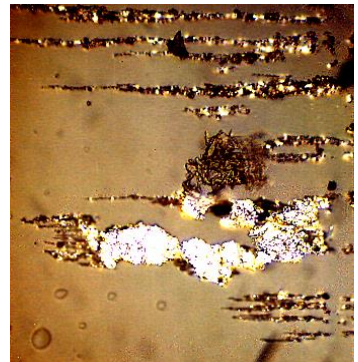
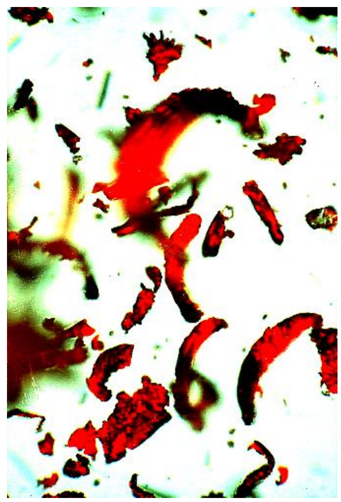


Fig. 3 Normal wear particles.	Fig. 4 Medium size normal wear particles.	Fig. 5 Big particles Normal wear particles.



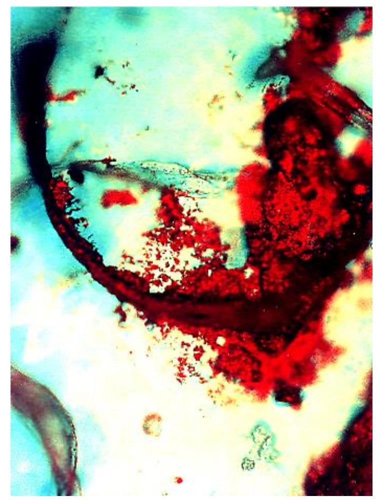


Fig. 6 Abrasive wear particles.	Fig. 7 Steel wear particles.	Fig. 8 Large abrasive wear particle.

Abrasive wear particles are generated when the relatively harder surface abrades the softer one. The embedment of relatively hard particles such as sand and oxide wear particles in the softer surface produces very fine machining swarf, removed from the harder friction surface. The common example of this mechanism is the embedment of abrasive particles in the surface of journal bearing which starts to abrade the shaft. The size of those particles is ranging from 2 to 5 µm wide and 25 to 100 µm long. They are considered as abnormal wear particles since detection of their massive generation signals the early failure of the component, Figs. 6 - 8.

The deformation of a soft surface by hard asperity or abrasive particle can be described by three different models shown in Fig. 9, [32, 33]. In the rubbing model, which is characterized by low friction, the relatively soft surface is plastically deformed forming a wave which is pushed away by the hard asperity. In the heavy rubbing wear model, which is characterized by high friction and high wear rate, a wave of plastically deformed material is removed producing wear particles. In the cutting model, the deformation of the friction surface proceeds by a microcutting mechanism and layers of material are removed as a chip.

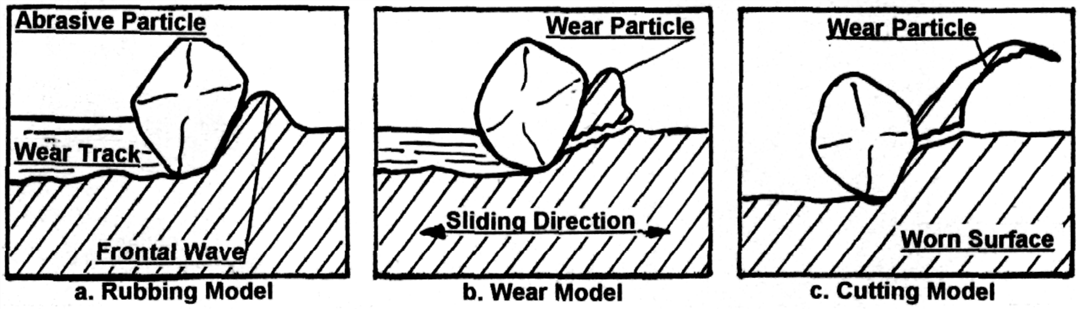


Fig. 9 Mechanism of abrasive wear.

Rolling fatigue wear particles are generated as a result of early failure of rolling bearing, Fig. 10. Their size is up to 10 μm. Their presence is detected before scuffing wear. Spherical particles are formed by deformation process where metal particles can be severely worked and rounded by the pressure build-up in the lubricant entrapped in the propagating surface fatigue crack, [34]. They are formed in deformed sub-surface material by sub-surface crack propagation, [35]. Also, they can be produced from chunky wear particles caused by adhesive wear and trapped in cavities in the sliding surfaces, Fig. 11. It become smoothed by burnishing processes, [36]. It was concluded that spherical wear particles are formed by frictional heating due to seismic motion of the friction surface, [37].

Contact fatigue failure is accompanied by the release of spherical particles. Several mechanisms have been postulated for the generation of spherical particles. These include fretting, abrasion, cavitations erosion, and fatigue-related processes, [38, 39]. A grinding operation was performed on a piece of low carbon steel a few feet from the Ferrograph. An aluminum oxide abrasive disc at a maximum surface velocity of 40 m/s was used, [40]. After only 2 minutes of grinding, the resulting Ferrogram contained thousands of particles of which more than 90 % were spherical.

Fig. 11 Spherical particles.

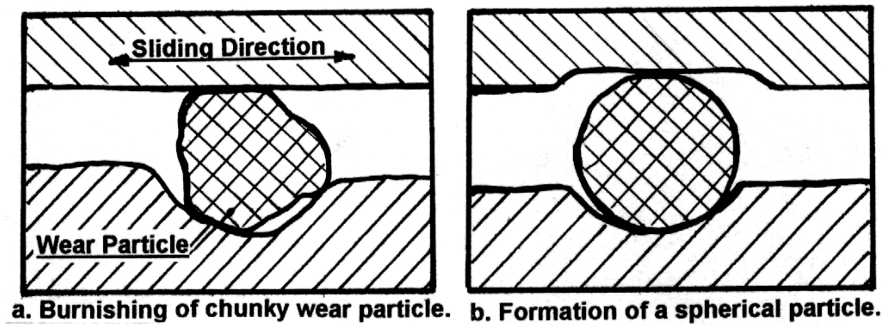


Fig. 11 Mechanism of formation of spherical particles.

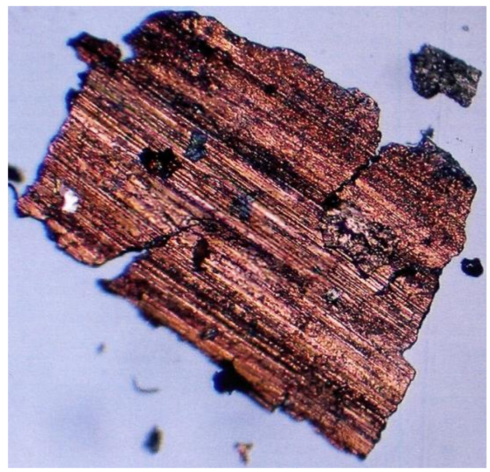


Fig. 12 Scuffing wear particles.	**Fig. 13 Fatigue wear particles.**	**Fig. 14 Chunky fatigue wear particle.**

Fatigue and scuffing wear particles signal the abnormality of wear. The fatigue wear particles are flat platelets of smooth surface and irregular circumference. Their size is ranging from 10 to 100 μm. They are generated from the friction surfaces of concentrated contact such as gears and rolling bearings. In severe sliding condition, wear particles have striations on their surface and straight edges, Figs. 12 - 15. Detecting such particles confirm that the load carrying capacity of the lubricant film is not enough and extreme pressure additive should be applied.

Fatigue wear is initiated by surface cracks. The mechanism of the surface crack is illustrated in Fig. 16. A primary crack originates at the surface at some weak point and propagates downward along weak planes such as slip planes. The primary crack can connect with an existing subsurface crack. When the developing crack reaches the surface, a wear particle is released, [41].

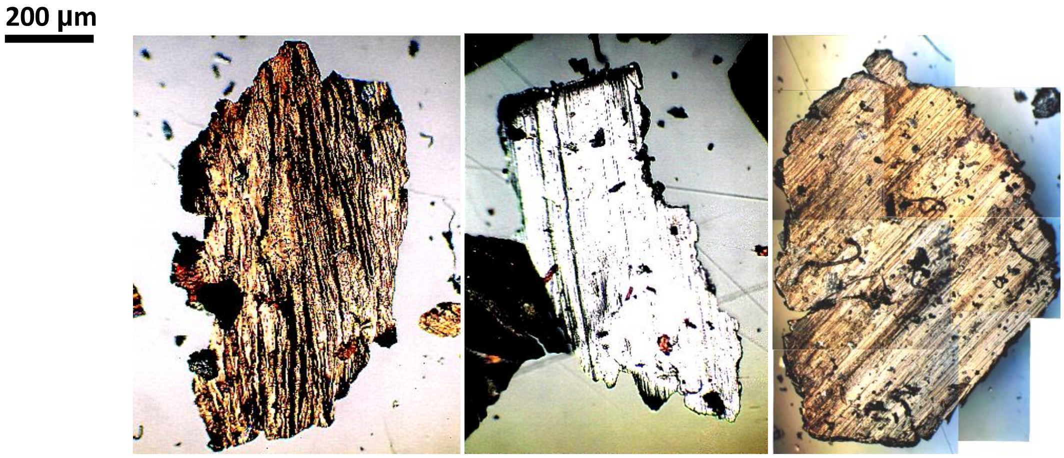


Fig. 15 Severe sliding fatigue wear particles of different sizes.

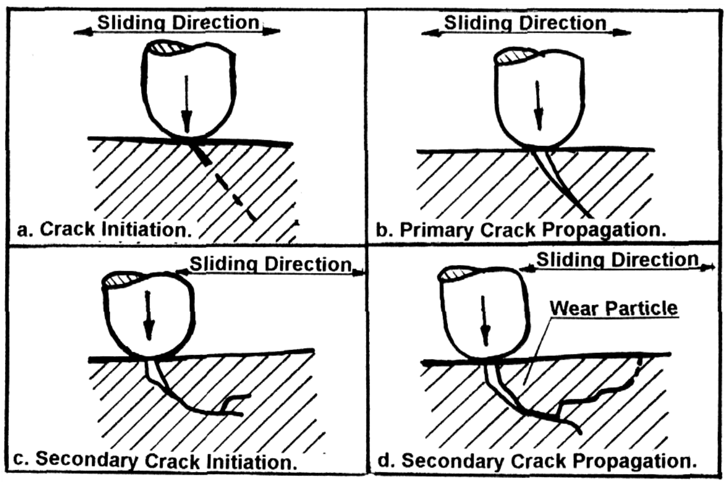


Fig. 16 Initiation and propagation of surface crack, [37].

It has been found that wear particles form due to the growth of surface initiated cracks, Fig. 17, when the sliding planes of weakness in the material become distributed parallel to the surface by repeated deformation process, [39]. Also, it was concluded that fatigue wear during sliding is a result of crack development in the deformed surface layer where the average thickness of the wear particles depend on the thickness of the deformed layer, [43].

Polymeric wear particles can be detected by Ferrography. Figure 18 displays some of those particles contaminating the oil, such as powder dispersion of lubricant additives like viscosity index improver, worn particles removed from oil seals and gaskets, and fibers removed from the filter elements. Abrasive sand particles deposited on Ferrograms prepared from oil samples taken from different machines are shown in Figs. 19 and 20. Their size is ranging from few microns to 70 μm. Their presence confirms the necessity of checking filter performance as well as cleanliness of fresh oil and indicates the severity of wear.

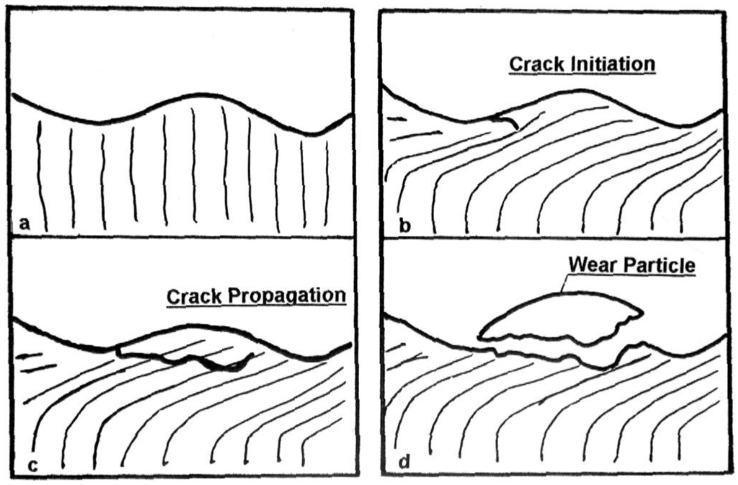


Fig. 17 Formation of wear particle due to surface fatigue, [38].

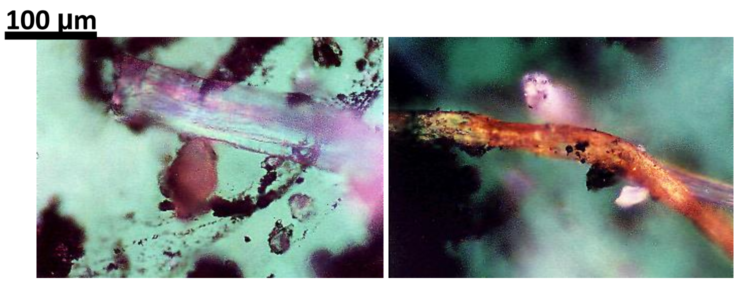


Fig. 18 Polymeric wear particles.

Fig. 19 Small abrasive particles.

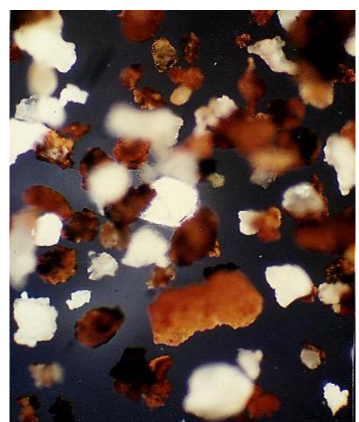


Fig. 20 Big abrasive particles.

CONCLUSIONS

The photomicrographs of Ferrograms illustrated in this work provide specific information to identify the wear and solid particles contaminating lubricating oils used in different applications. This information can help in identifying images during the visual inspection of those particles by microscope and the description of wear mechanism which generates those particles. Furthermore, the transfer from one wear mechanism to the other and the abnormality of wear can be identified. It offers a guide to interpret the data obtained during

the study of tribological problems such as friction, wear and lubrication as well as developing filtration technology. Furthermore, it helped in considerations for exercising predictive maintenance and condition monitoring of the machinery.

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