EGTRIB Journal
JOURNAL OF
THE EGYPTIAN SOCIETY OF TRIBOLOGY
VOLUME 10, NO. 3, JULY 2013, pp. 41 - 50 ISSN 2090 - 5882

TEMPER COLOURS OF WEAR PARTICLES

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ABSTRACT
In the present work, wear particles, retained by oil filter of an internal combustion engine, were examined by optical microscope to reveal details of size, shape and quantity of particles. The temperature of the moving surfaces inside engines can be determined by observing the temper colours of the wear particles. Because of the electronic mechanism of oxidation, the optical interference of the oxide film formed on the surfaces of wear particles can give rise to the appearance of colours depending on the thickness of the film. The rate of oxidation and therefore the thickness of the oxide film is determined by the crystallographic orientation of the substrate metal.

Based on the observations in the present work, it can be suggested that the sliding surfaces of the engine were suffered from severe micro-cutting process. The presence of the surface striations confirms the evidence of abrasive wear, where the rise of temperature might be attributed to the severe friction and the micro-cutting process caused by excessive abrasive particles contaminated in the lubricant and embedded in the sliding surfaces. The change of the temper colours of wear particles might be from temperature rise caused by extra friction as well as the abrading action of abrasive particles into the sliding surfaces.

KEYWORDS
Wear particles, oil lubrication, engines, temper colours, wear severity.

INTRODUCTION
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, [1]. 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.

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 nanoparticle strengthened nickel-based brush plating composite coatings were prepared by co-deposition of nanoparticles with Ni metal–matrix, [2]. 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, [3 – 7]. A diagnostic technique that can estimate quantitatively wear amounts under lubricated condition was developed using developed on-line particle counter, [8]. 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, [9, 10]. 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, [11]. 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, [12]. 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 [13], the volume fraction of abrasive in the slurry [14], the abrasive particles, the materials of ball and specimen, and the ball surface condition [15]. 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, [16 - 20], 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, [21, 22].

The wear and friction of cylindrical contacts caused by lubricant abrasive contaminants is reported, [23]. 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, [24]. 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, [25], 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, [26]. 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, [27]. 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, [28]. 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, the temper colours of wear particles retained by oil filter of automotive engine were examined by optical microscope to monitor the working conditions and have specific information about wear mechanism prevailed.

EXPERIMENTAL

Wear particles were examined using optical microscope. The examination of wear particles, retained by the oil filter disassembled from the tested engine, was carried out to determine the wear mechanisms, which occurred during the operation of the tested engine. 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.

RESULTS AND DISCUSSION

The effect of temperature on the formation of oxide layers on wear particles surface was studied, [28]. When the temperature exceeds 200 °C further growth of the oxide film takes place by diffusion of metallic ions on the metal oxide interface outwards through the oxide film. Electrons tunneling from the metal through a thin oxide film are captured by oxygen adsorbed on the oxide surface until an equilibrium becomes established. The field set up by these trapped electrons can then pull ions through the oxide film. The growth rate is limited either by the tunneling of electrons or by the rate of ion drift. The rate of growth of oxide films is usually logarithmic, [29]. The most probable explanation for this is that the potential induced across the film gives rise to a potential gradient which is reduced as the film thickness increases. Based on the electronic mechanism of oxidation, the oxide film formed is uniform in thickness and in optical properties so that optical interference can give rise to the appearance of colors depending on the thickness of the film. This has been used traditionally in the form of temper colors which appear on tool steel in the temperature range 200 - 340 °C. They range from a faint straw color at 204 °C through a bronze to a blue at the highest temperature.

The temperature of formation of temper colors differs for different alloys and thus provides a means for their identification. The mode of illumination of the particles was performed by white reflected light and green transmitted light, [29]. Heating AISI 52100 to 330 °C and subsequently to 400 °C showed a distinctive blue color at 330 °C with a subsequent fading to a grey color at 400 °C. Nickel particles, when subjected successively to 330 °C and 400 °C, showed no discoloration. However, on heating to 480 °C the nickel particles became bronze or blue. On subsequent heating to 540 °C all the particles became blue or a faded grey. AISI 304 stainless steel starts oxidizing at a lower temperature than that for nickel, with some particles showing a faint yellow color at 400 °C. However, the rate of oxidation of stainless steel at higher temperatures is lower. It was noted that even at 540 °C none of the particles has developed a completely blue color. Very small particles usually found below 50 μm did not always develop interference colors. This may be because the film area was insufficiently wide to reflect sufficient light to register optically or because the particles had insufficient thickness for the required oxide layer. In the latter case the particles become transparent and will

transmit light. The alloys that show different colours at different temperatures are all magnetic. The majority of non-magnetic engineering alloys do not display temper colors.

Examination of the surface of wear particles using an optical microscope is shown in Figs. 1 - 5. 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. Large high alloy steel wear particle is shown in Fig 1. A distinctive blue colour (330 °C) with a subsequent fading to an orange colour (400 °C) is illustrated. The presence of striations of pink (up to 540 °C) temper colour is indicative of abrading action of the hard asperities of the counterface. This is a 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 is propable.

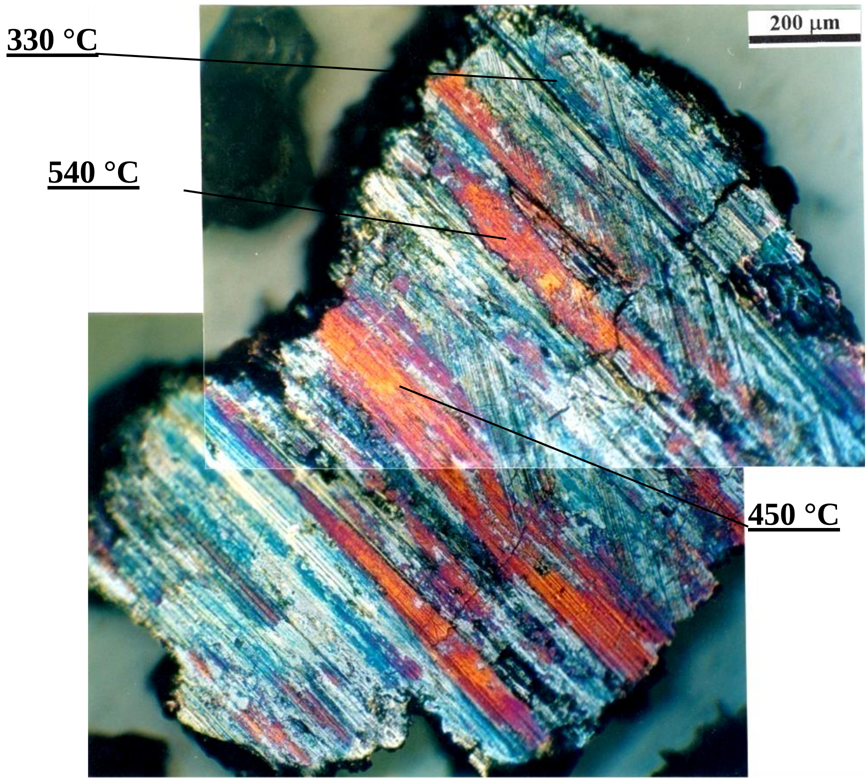

Fig. 1 Severe wear particle of alloyed steel.

Metallic and nonmetallic wear particles are shown, Fig. 2. Severe wear particle of different colours caused by the frictional heating. The colour variation of this particle, from red (540° C) to orange (400° C) to blue (330° C), shows the temperature distribution of the worn surface. The temperature increase is directed upward regardless the direction of the striation marks. The removal of such particle may be caused by surface fatigue indicated by the straight edges.

The temper colours of alloyed steel wear particle, Fig. 3, indicated that the temperature increased up to 400° C, except the localized zone of blue colour, where the temperature increased up to 330° C. Presence of surface striations of red colour confirmed that the temperature exceeded 540° C. The temperature increase may be caused by the severe

abrasive wear mechanism prevailed either by the abrasion of the relatively harder asperities in the counterface or from the embedded abrasive particles.

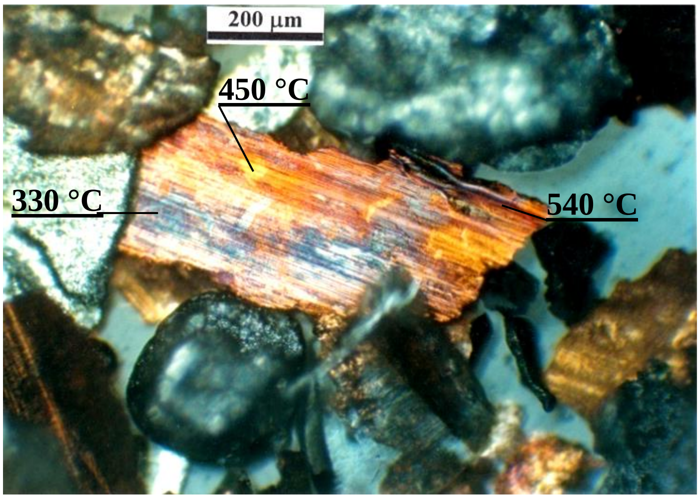

Fig. 2 Metallic and nonmetallic wear particles.

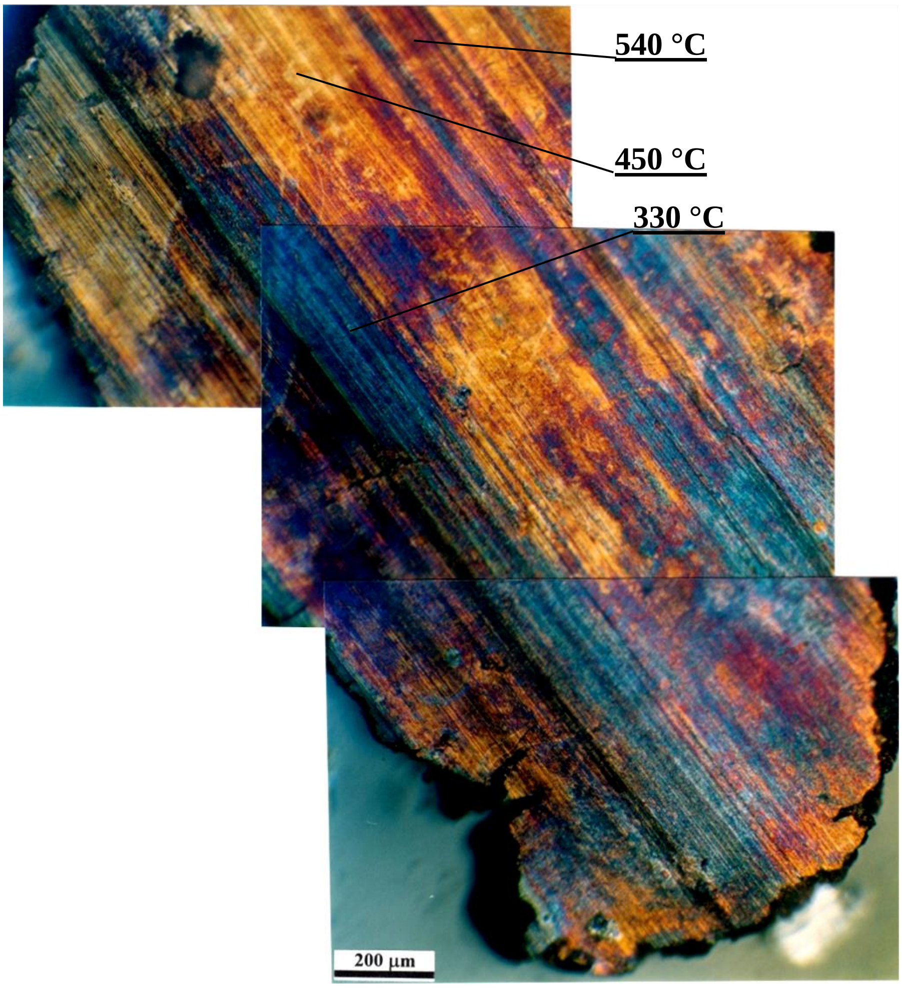

Fig. 3 Alloyed steel wear particle.

Wear particle shown in Fig. 4 is of surface striation indicating severe sliding. Those striations were caused as a result of inefficient lubricant or lack of lubrication. A distinctive blue colour (330 °C) with a subsequent fading to an orange colour (480 °C) is evident. This is catastrophic sliding wear mode, which is indicative of failure of the surfaces. The excessive surface shear stresses indicated by the straw and mottled bluing are confirmed by the abrasion marks on the surface of wear particle caused by relatively harder asperities of the counterface.

Severe wear particle of alloyed steel is shown in Fig. 5. Some of blue (330 °C) and pink (480 to 540 °C) colour as well as some dark metallic oxides are shown as a result of the excessive heat and/or lubricant starvation during particle generation. The diameter of the contact asperities of the counterface can be determined from the width of the longitudinal scratches shown on the surfaces of wear particles. It can be seen that the temper colours of the wear particles indicate the severity of sliding condition of the engine and signal that the engine suffered from the lack of lubrication and/or inefficient lubricant additives.

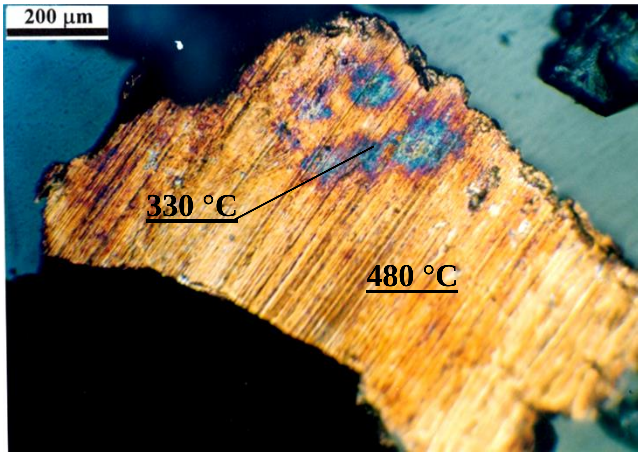

Fig. 4 Fatigue wear particle of low carbon steel.

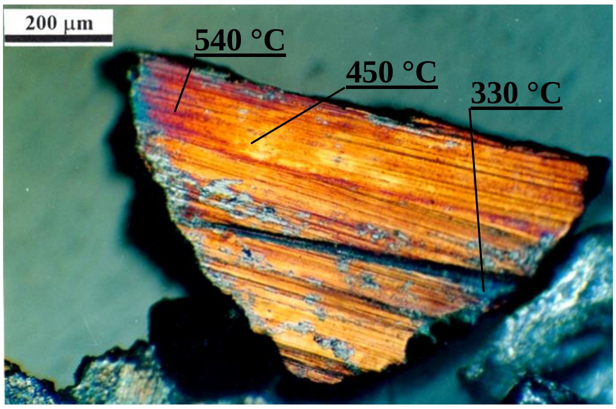

Fig. 5 Severe wear particle of high carbon steel.

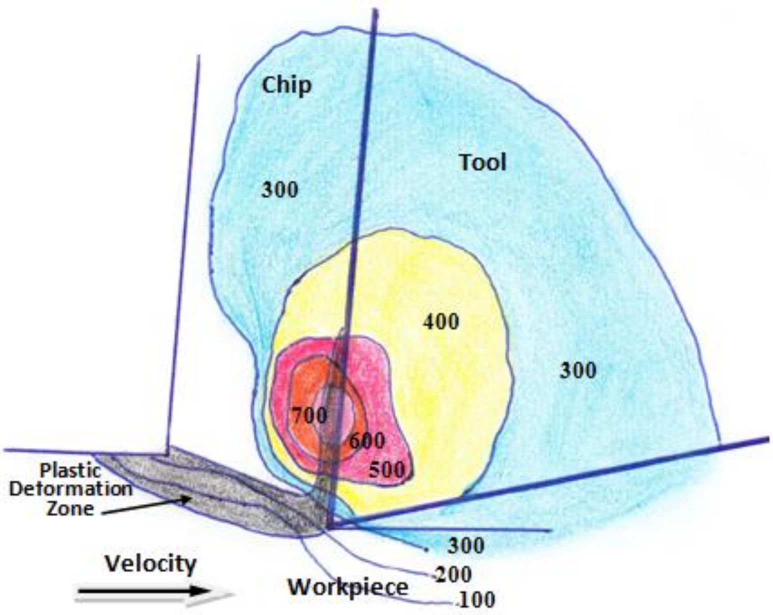

Fig. 6 Temperature distribution in the cutting tool, chip and workpiece.

Based on the observations in Figs. 1 – 5, it can be suggested that the surfaces of the engine were suffered from severe micro-cutting process. The presence of the striations confirms the evidence of abrasive wear, where the rise of temperature might be from the severe friction. On the other point of view, it can suggested that the rise of temperature might be attributed to the micro-cutting process caused by excessive abrasive particles contaminated in the lubricant. In material cutting, all of energy dissipated in plastic deformation is converted into heat so that the temperature in the cutting zone increases. Based on the fact that heat generation is related to the plastic deformation and friction, the main sources of heat when cutting are plastic deformation by shearing in the primary shear zone, plastic deformation by shearing and friction on the cutting face and friction between chip and tool on the tool flank. The results showed that increasing cutting speed, feed rate and depth of cut resulted in increase in the temperature at the back rake surface, [30]. However, cutting speed had the most influence on the temperature. Therefore, it is understood that the highest temperature is observed on the cutting tool surface a bit away from the cutting edge. Temperature distribution in the cutting tool, chip and workpiece obtained by the finite element analysis is shown in Fig. 6. The maximum temperature may reach 700 °C. The change of the temper colours of wear particles might be from rise caused by extra friction as well as the abrading action of abrasive particles into the sliding surfaces.

CONCLUSIONS

The present study proposes method that can be applied to detect the temperature rise in the engine surface. With the knowledge of the materials used in the construction of the engine the source of wear could be identified. Besides, it provides an insight into the severity and abnormality of the wear process. Besides, inspection of the temper colours of wear particles will enable the detection of a critical operation of the engine through knowing the maximum surface temperatures during the generation of the wear particles. Based on the inspection of wear particles the present work can be applied to monitor the condition and performance of the internal combustion engine by determining the working temperature of the moving surfaces. Besides, wear mechanism

responsible for the abnormality of the wear particles and diagnosis of engine failure can be revealed. It is recommended to use the materials that are sensitive to temperature variation to be used as coating on such surfaces subjected to high temperature.

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