ANALYSIS OF WEAR RATE OF INTERNAL COMBUSTION ENGINE USING FERROGRAPHY TECHNIQUE

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Abstract - *All types of machines and parts get worn out due to continuous usage and working. Proper maintenance and routine checks are necessary to ensure that the machines work for a longer time. Some important components of an engine are piston, piston rings, cylinder head, liner etc. where major wear takes place. In this present work, a four stroke single cylinder petrol engine is analysed to monitor the condition of engine components i.e. how the wear rate is taking place with vehicle run and for this Wear characteristics, both quantitative and qualitative, have been studied by Ferrographic analysis of collected lubricating oil samples from the oil sump at different distances of engine run. Images of the wear particles have also been taken using CCD camera. The presence of various types of wear particles gives the information about the wear rate of engine components at different runs. Also it is found that during initial run of engine the wear particles concentration was more up to certain distance but decreases and found in less quantity.*

This technique allows a predictive maintenance of the engine components to be carried out, as it allows for possible breakdowns to be detected prior to a serious failure being produced.

***Keywords*: Wear, Engine, Wear Debris Analysis, Ferrography.**

1. INTRODUCTION

During the operation of the machinery, wear occurs whenever there is interaction between moving surfaces, which causes the formation of wear particles from the moving parts resulting in their continual degradation. Wear is an unavoidable phenomena of surface contact between engine parts like piston, cylinder, piston rings, cylinder head etc. Engine components life cycle, safety factors, performance ratings and maintenance schedule are predicted on normally occurring wear. The various techniques for wear characterization of internal combustion engines are Atomic absorption spectrometry (AAS) of lubricating oil samples from engine and Ferrography Technology of used lubricating oil drawn from lubricating oil sump. These methods of oil analysis provides advanced warning of abnormal wear in high value critical assets can provide important options otherwise unavailable to decision-makers. Secondary damage may be avoidable by identifying and removing the worn parts, and therefore reducing subsequent maintenance costs that would result if a catastrophic failure were to occur. In addition, a better understanding of the nature of the problem can be obtained, reducing uncertainty about maintenance procedures.

Wear in most cases occurs through surface interaction at asperities and is a complex process influenced by a number of factors including the metallurgy of contacting materials, surface texture, operating conditions of the components, load, speed, temperature, environment, and lubricant formulations [1]. The wear process is generally quantified by wear rate, which is defined as the volume or mass of material removed per unit time or per unit sliding distance. There are several studies were conducted to study the engine components wear between different pair of contacts. V. Macia´n et.al. [2] In this paper, an analytical approach to enable a more accurate wear determination from engine oil samples is developed. The factors like oil consumption, fresh oil additions, etc., and particular features such as engine age, type of service, environmental conditions, etc. are taken into account and an improved maintenance program for internal combustion engines based on oil analysis is developed. In the year 2005 they studied failures in Diesel engine fuel injection systems by applying ferrography as technique and there is a technique is described to detect failures in the operation of the fuel injection systems in Diesel engines [3].In the year 2008 N Govindarajan and R Gnanamoorthy [4] studied about the fatigue phenomenon which is a most common failure seen in the structural components which are subjected to fatigue load/ cyclic loads such components like ball bearings , mating gears etc. for this lubrication oil is collected for regular intervals and ferrography test is involved to predict the wear rate of powder metallurgy steels. L. Gara et. al. [5] In this paper Cylinder liner wear rates of single cylinder of diesel engine is measured by replication method were consistent with long-term wear observed in different tests of diesel engines. Liu Tonggang et. al. [6] there is a proposed of method of qualitative ferrographic analysis by quantitative parameters of wear debris characteristics. Manoj Kumar et. al. [7] discussed the difficulties in identifying wear particles and finding out the exact health of equipment, which, due to its subjective nature, is influenced by human errors and also the Advancement and current status of wear debris analysis for machine condition monitoring. In 2009, Surojit Ghosh et. al. [8] studied Ferrographic analysis of industrial machineries lubricating oil with a view to automated maintenance approach. K.N.V. Subrahmanyam [9] experimentally investigated various types of wear particles by Ferrographic analysis which can detect wear of various components well in advance. In the year of 2000, M.Priest and C.M. Taylor [10] performed their study on automobile engine tribology. They focused on tribological design and friction involved with the tribological components of the engine with special attention upon surface topography and surface interaction considerations.

However, in this present work a single cylinder, four stroke, air cooled petrol engine is studied to find out the wear of engine components and for this lubrication oil samples from oil sump of engine is collected at different interval of vehicle run. After collection of lubricating oil samples these samples were analysed by ferrography technique to identify the concentration of wear particles, their shape and size etc. in each sample. The results indicates that when the engine was new and up to certain distance of vehicle run the presence of wear particles or wear particle concentration was more but after some distance wear particles found was in very less quantity this means that that initially for any engine wear rate is more but later it is not of much concerned.

2. WEAR PARTICLE ANALYSIS

Wear is basically the damage to any surface that generally involves sufficient loss of materials and it may occur as a result of relative motion between that surface and contacting substances. Wear particle investigations and fault diagnosis of different machineries or engines are not a new topic in maintenance engineering rather in the field of tribology. This technique has already been accepted as an effective and economic method to detect the actual condition of engine. Also, preventive maintenance strategy can be performed on machines if it applies properly [11]. Due to some shortcomings in traditional wear analysis, digitized image vision has become one of the solutions for the problems associated with conventional techniques, especially in case of offline condition monitoring. Wear mechanism has been classified in several ways by many researches or industry people. Wear mechanism depends mainly on the two surface in contact to each other. Basically, there are two types of wear occur in any machine interaction i.e.

- Mechanical wear (Associated with friction, abrasion, impact and fatigue)
- Chemical wear (it attacks the surface by reactive compounds and subsequent removal of products of reaction by mechanical action)

It is a quite well known phenomenon that lubrication is one of the best methods of detection of wear amongst other techniques, but wear particle distributions may be characterized based on the features such as;

- Material
- Size
- Shape
- Concentration

Wear particles can be simplified as normal particles, fatigue particles, sliding particles, characteristics particles a turning in condition, red oxides, black oxides, cutting particles ball particles, wear polymerides, particles from corrosive wear, impurities, nonferrous particles and etc. [12]

3. TYPES OF WEAR PARTICLES

These are the basic wear particle types for ferrous and nonferrous particles that generates through the wear out progress. Normal rubbing wear particles (Fig 1) are generated as the result of normal rubbing wear in a machine. Rubbing wear particles consist of flat platelets, generally 1-15 microns or smaller. There should be little or no visible texturing of the surface and the thickness should be one micron or less. Cutting wear particles (Fig.2) are generated as a result of one surface penetrating another. There are two ways of generating this effect. A relatively hard component can become misaligned or ractured, resulting in hard sharp edge penetrating a softer surface (5-100 micron particles). Very fine wire-like particles can be generated with thickness as low as .25 microns due to the presence of abrasive contaminants. Cutting wear particles are abnormal. If a system shows increased quantities of large (50 micrometers long) cutting wear particles, a component failure is potentially imminent. Severe sliding wear particles (Fig.3) are identified by parallel striations on their surfaces. These are produced from surfaces undergoing high stress due to high speed/load and inadequate lubrication in the components. They are generally larger than 15 microns in size. Bearing Wear particles (Fig.4) generated as a result of fatigue in rolling element bearings and sleeves of journal bearings. These can be fatigue particles as well as laminar wear particles.

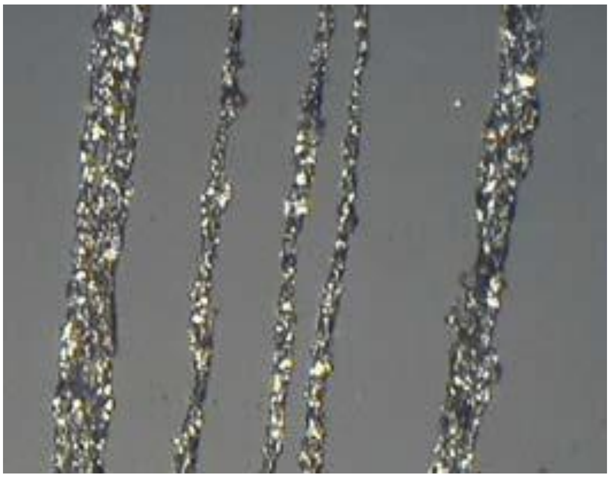

Fig.1: Normal rubbing wear

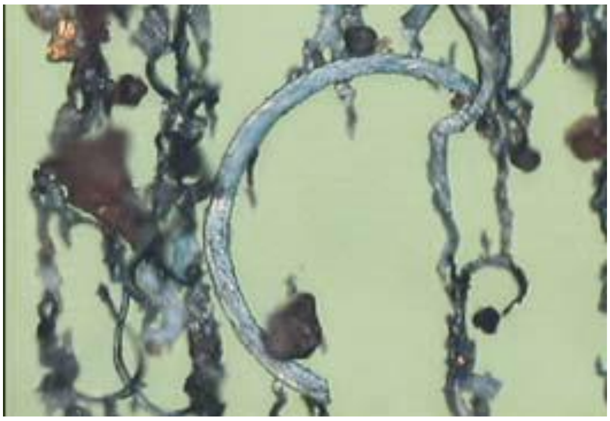

Fig.2: Cutting Wear

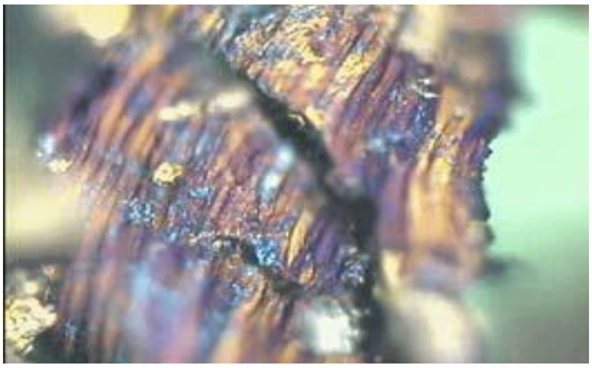

Fig.3: Severe sliding wear

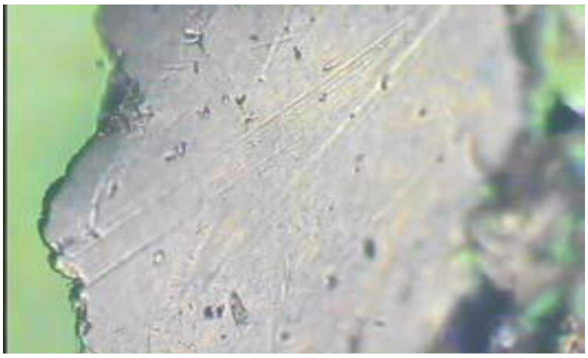

Fig.4: Bearing wear

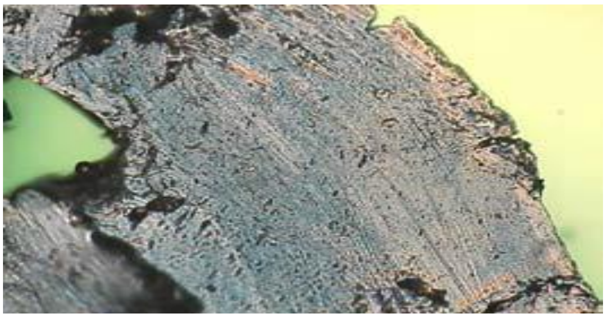

Fig.5: Gear Wear particle (Pitch line fatigue)

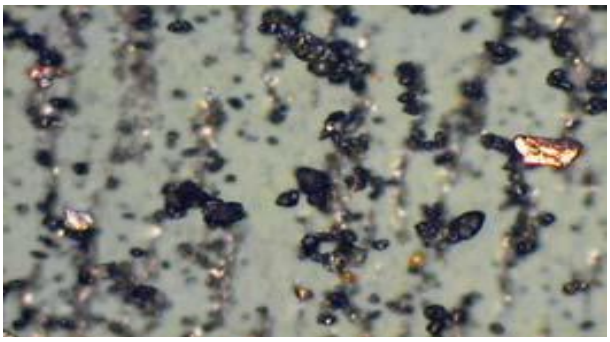

Fig.6: Black Oxides

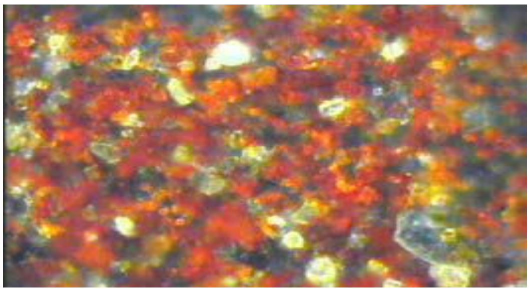

Fig.7: Red Oxides

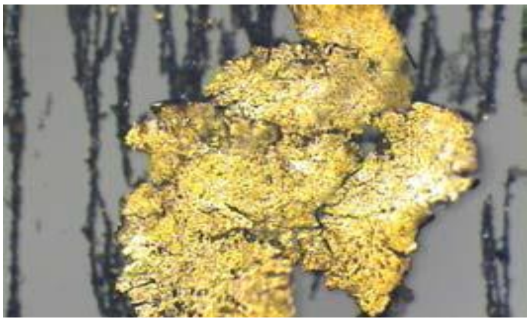

Fig.8: Copper alloy Particle

Gear wear particles (Fig.5) generates in two ways, Pitch Line Fatigue Particles from a gear pitch line have much in common with rolling-element bearing fatigue particles. They generally have a smooth surface and are frequently irregularly shaped. The chunkier particle result from tensile stresses on the gear surface causing the fatigue cracks to propagate deeper into the gear tooth prior to spalling. Scuffing or Scoring Particles are caused by too high a load and/or speed. The particles tend to have a rough surface and jagged circumference. Black oxides (Fig.6) are associated with insufficient lubrication between metal surfaces. Particles are formed under high temperatures as result of metal to metal contact. Red oxides (Fig.7), commonly termed as rust associated with water contamination. Non Ferrous metals (Fig.8) generally found in equipments and identified in ferrography may include aluminium, copper alloys and Babbitt metals. Sand/dirt, fibers and other contamination can be identified in ferrography. Sand/dirt can be from outside contamination of the lubricant. Sources can be from improperly cleaned systems, faulty seals and breathers etc. Fibers can be from ruptured filters etc. Evaluation of the health condition of the engine is purely subjective based on the following. Engine being monitored, morphology of particles that includes size of the particles, shape of the particles, surface structure, concentration and orientation of the particles and wear particles concentration.

4. WEAR MEASUREMENT TECHNIQUES

Ferrography is a technique for the collection and determination of the concentration and morphology of wear particles suspended in lubricants [13, 14]. Ferrography techniques have been found as one of the suitable measurement techniques of wear debris. It may provide the sufficient characteristics of particles, so that the operation wear modes within machines may be determined. It can allow the prediction of imminent behaviour of engine. It can be used routinely to monitor the condition and wear of the vital components at higher risk. Generally to typical types of measuring techniques are quite popular like Direct Reading (DR) and Analytical Ferrography. But in the present work, direct reading has been utilized as the operational mode. With the help of DR instrument, the density of large particles (DL) and the density of small particles (Ds) can be measured very easily. On the basis of those parameters, the values of wear particle concentrations and percentages of large particles can be detected. By performing quantitative analysis of wear particles, the possible mode of wear generation can be detected. Based on the detection of wear, the further course of action for maintenance of equipment can take place [15]. The number of wear particles can be mathematically deducted by using the relationship,

Severity Index(S.I.=(DL+DS)(DL-DS)=(DL2-DS2) Where DL = Number of larger particles, DS = Number of smaller particles, DL+DS = Concentration of solution, DL-DS=Size distribution. The values of the DL and DS are determined by measuring the blockage of light using fiber optics at the locations of large particles and small particles.Trending of the DL and DS readings reveals changes in the wear mode of the system. For example, an increase in the DL value indicates that the system has entered into an abnormal wear mode. In comparison, an increase in the DS value can indicate an increase in system corrosion. And the expression I=(DL2-DS2) reflects the severity of abnormal wear.

Fig: 9 DR instrument and Dual ferroanalyzer

Based on quantitative analysis, qualitative analysis can also be done by using Dual Ferroanalyzer as shown in figure 9. It is basically the ferrogram making instrument (fig10), where dual side makers are available.
It should be used with maximum equipment utilization in wear analysis. For better handling, independent places have been provided where two samples can be prepared concurrently. In the present work, the ferrograms of used oil from oil sump of engine have been prepared by this instrument.

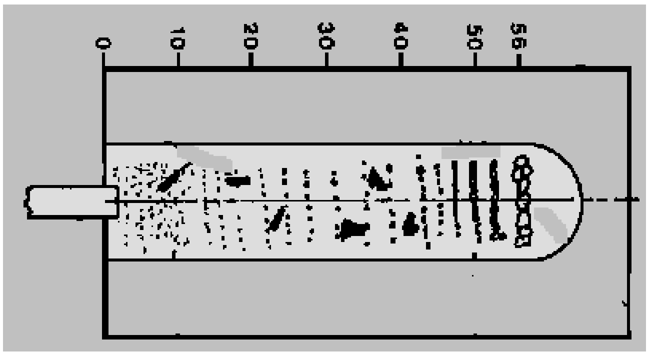

Fig10: Particles deposition in the ferrograms

Quantitative ferrographic analysis is easy for analyst to determine the wear condition trend of a lubrication system, however, the information of debris morphology (size, shape, colour and surface texture, etc.) have been neglected. So when an abnormal wear is detected, qualitative ferrographic analysis is needed for more details. Qualitative ferrographic analysis of wear particles is a very effective means of oil analysis for machine condition monitoring and fault diagnosis. In examining the ferrogram, a trained analyst can determine the type of wear occurring in the system and the cause of such wear by the debris morphology under bi-chromatic microscope. Basically there are three types of equipment can be used in ferrography namely, Direct Reading (DR) Ferrograph, Analytical Ferrograph and Ferroscope. There are two approaches for ferrographic analysis, qualitative approach and quantitative approach,. Qualitative approach means size distribution, detection of all wear debris categories, providing the useful information about debris characteristics, fault diagnosis of the engine and quantitative approach includes providing useful information about operating condition of engine for debris characteristics, severity index determination. But mainly qualitative approach is taken into consideration for ferrography is this present study.

5. EXPERIMENTAL PROCEDURE

In the process of Wear Debris Analysis, the wear particle identification through the microscopic examination plays a very important role. The accurate observation of the Wear particles generated from the lubricated components of the equipment will correctly predict the internal wear condition of the machine .The steps of wear debris analyses (WDA).

- Sample collection
- Codification
- Physical and Chemical test

0-4	NORMAL WEAR
5-7	MARGINAL WEAR
8-10	CRITICAL WEAR

- Incubation
- Slide preparation
- Microscopic examination
- Report generation

The samples for investigation are collected from the Honda service centre. Investigation works for this dissertation are carried out on Honda shine bike. Following Table shows the technical specification of Engine and details list of all samples or engine oil are used for the investigation.

Table 1: Technical specification

Engine (Honda shine)	
Type	Air cooled ,4 stroke , SI engine
Displacement	124.7cc
Max net power	7.88 kW (10.57 bhp) @7500rpm
Max net torque	10.30 Nm @ 5500 rpm
Bore	52.4 mm
Stroke	57.8 mm
Max speed	93 kmph

Table 2: Details of samples

S No.	Sample code	Vehicle run (Km)
1	S1	1495
2	S2	3036
3	S3	7260
4	S4	12065
5	S5	20760

The above collected samples were tested using ferrography technique and from the report generated the following results like types of wear particles present in oil, wear rate of engine components, wear particles concentration in each sample , condition of engine after certain interval of run etc. obtained.

6. RESULTS AND DISCUSSION

After the samples were tested and based on the wear debris present in the lube oil the machine condition is rated according to types of wear particle present, their sizes and concentration in the rating scale as:

On a subjective scale of (0-10)
Thus based on above ratings following rating graphs with different types of particle in different samples are observed as follows :

Ferrous wear particles (S1- 1495)

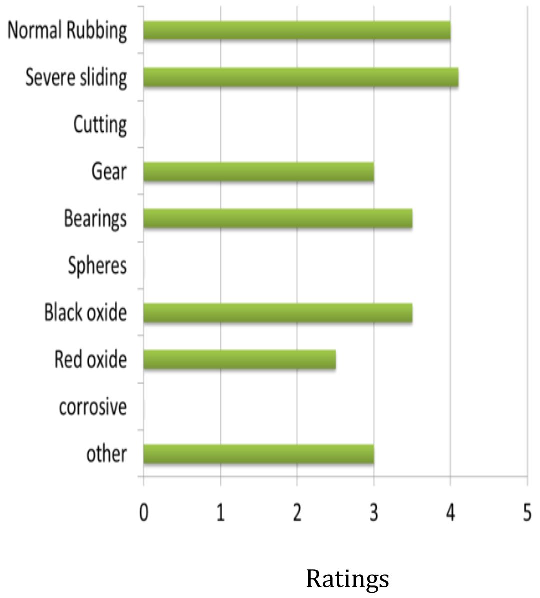

Fig 11: Graph between different wear particles and their ratings in S1.

Ferrous wear particles (S2-3036)

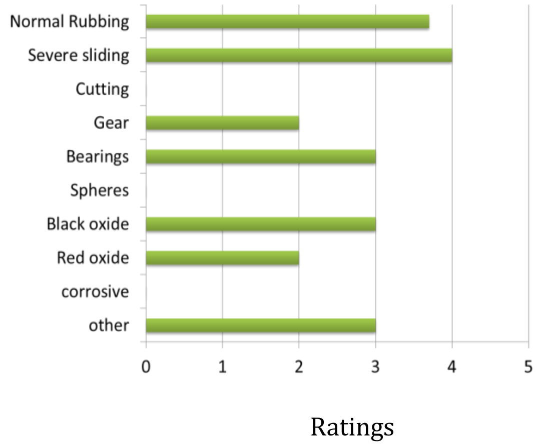

Fig 12: Graph between different wear particles and their ratings in S2.

Ferrous wear particles (S3-7260)

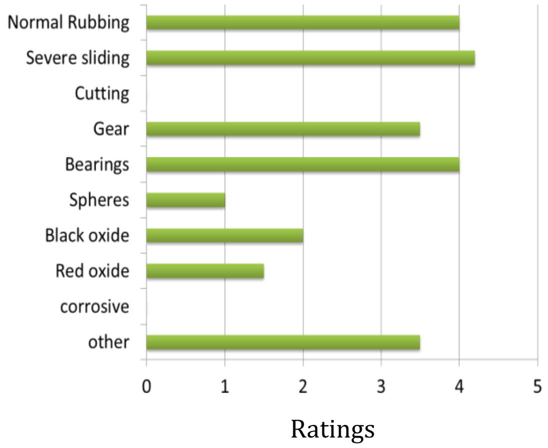

Fig 13: Graph between different wear particles and their ratings in S3.

Ferrous wear particles (S4-12065)

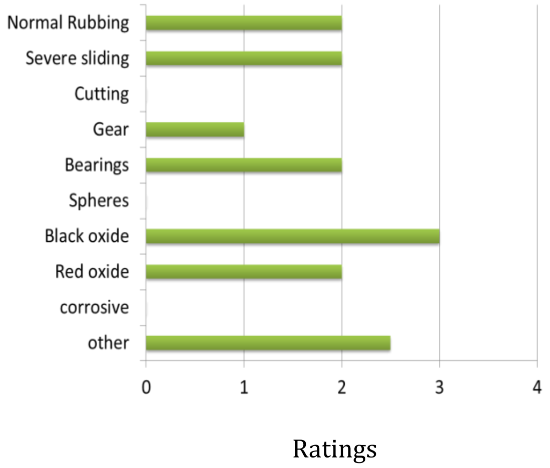

Fig 13: Graph between different wear particles and their ratings in S4.

Ferrous wear particles (S5-20760)

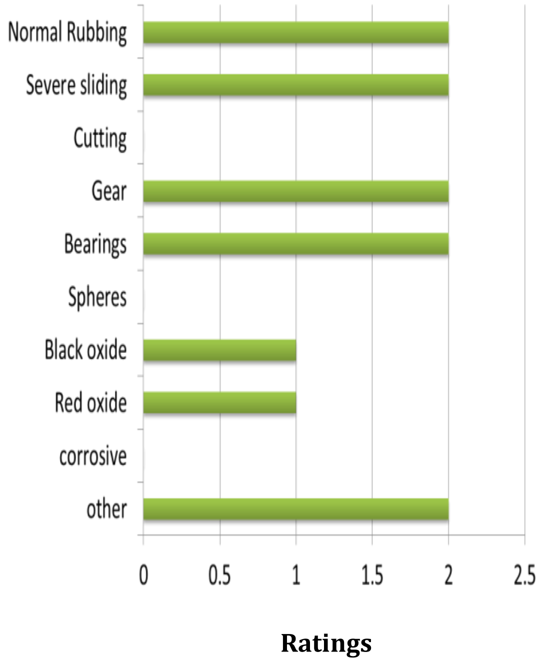

Fig 15: Graph between different wear particles and their ratings in S5.

From fig.11,fig.12&fig.13 shown above it is observed that during initial run of vehicle say up to 7-8 thousands(approx.) of kilometres or in S1,S2,&S3 the concentration of wear particles such as Normal rubbing particles, severe sliding wear particles, gear particles, bearing particles etc. found is near marginal quantity this means that initially wear out of the engine components was more but after some distance of engine run as shown in fig.14 &fig.15 wear particles found was under normal condition it means wear of components is less comparing with initial conditions. This can be explained from Archard's theory of sliding wear[16] that initially when adhesive energy in magnitude is more that causes more and large wear particles but after continuous use of those components residual elastic energy overcomes the adhesive energy a fragment forms a loose fine particles, similarly in engine components also initially due to high adhesiveness between components causes more wear but later due residual elastic energy stored causes less wear. Also may be due to chemical changes in the fragment due to oxidation may reduce adhesive strength and enhance formation of loose particle.

Non Ferrous wear particles

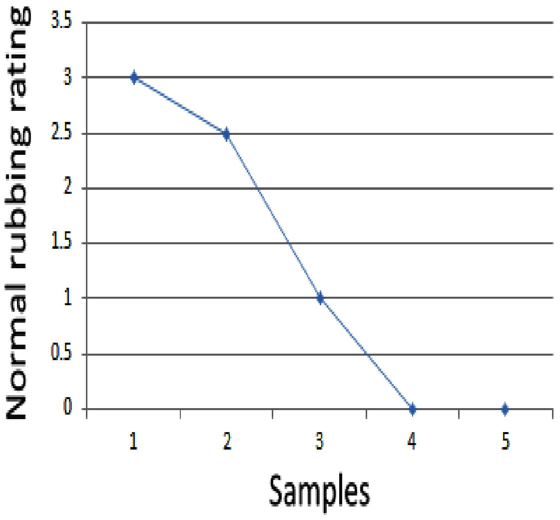

Fig. 16: Graph between Normal rubbing rating of Non ferrous materials with vehicle run.

From the graph it is observed that Normal rubbing wear particles of non ferrous materials such as (copper, aluminium etc.)are in very less quantity and decreasing with vehicle run and even after sometime there is no presence of such particles as in sample 4& 5.

Wear particle concentration

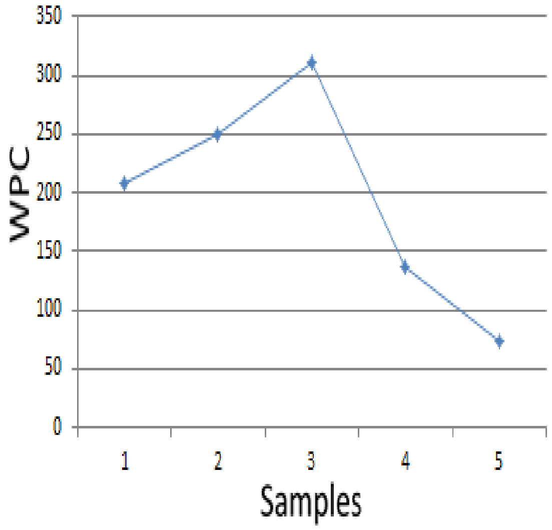

Fig.17 : Graph between wear particle concentration with vehicle run.

From fig.17 ,WPC (the total number of particles in unit volume of oil sample is assumed as wear particle concentration) is found initially increasing and near limited value of 500 but with vehicle run it has very low concentration of wear particles.

Low alloy steel (severe sliding wear particle)

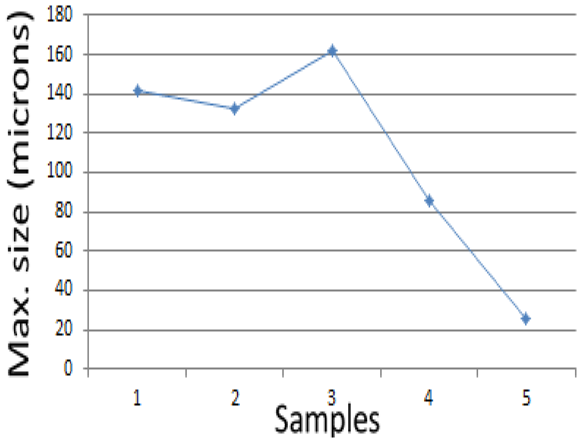

Fig.18: Graph between maximum size of low alloy steel sliding wear particles with vehicle run.

Low alloy steel severe sliding particles these element found could be of piston ring, gear, cam etc. and the above fig.18 shows that how initially there is severe wear of these components but after a certain vehicle run their maximum size observed decreasing but the presence of these particles in all samples shows that there is continuous wear of piston ring. Excessive sliding stress on the ferrous components (gears, cams, cam rollers ,etc.) is also indicated by the presence of marginal quantities of low alloy steel sliding wear particles during initial run of vehicle.

Case hardness steel wear particles

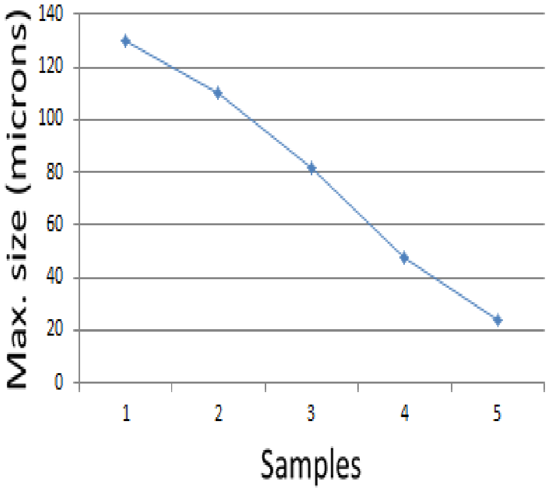

Fig .19: Graph between max. size of case hardness wear particles with vehicle run.

Case hardness steel particles are of piston pin and from the fig.19 it is observed that the maximum size of these particles initially this shows that there is more wear of piston pin and this due to sliding and rolling motion between piston pin and connecting rod.

Bearing wear particles

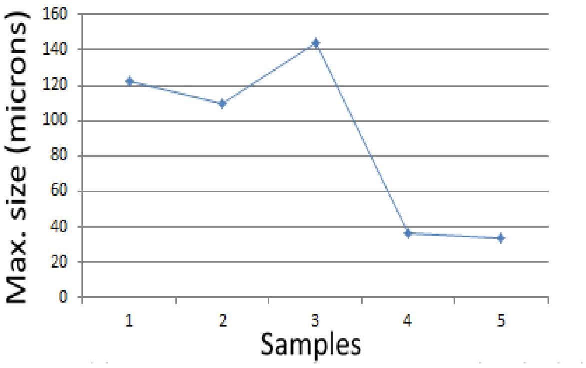

Fig .20: Graph between Max. size of bearing wear particles with vehicle run.

Bearing wear particle (could be from crankshaft /connecting rod main bearing) and maximum size found increasing up to sample no. 3 but there is sudden decrease in their sizes. It shows initial wear rate of bearings was more but decreased after sometime.

In well-lubricated rolling element bearings, there is no progressive wear due to adhesion or abrasion but bearing life is limited by fatigue. Although no direct contact occurs, the mating surfaces experience large stresses transmitted through the lubricating film during the rolling motion .In the presence of such stresses, the maximum compressive stress occurs at the surface but the maximum shear stress ,the position of first yield ,occurs at some distance below the surface . As rolling proceeds, the directions of the shear stresses for any element change sign and this is almost entirely responsible for energy dissipation in rolling contacts .If the stress amplitude is above the fatigue limit of the bearing material, fatigue failure will occur .

White non ferrous wear particles

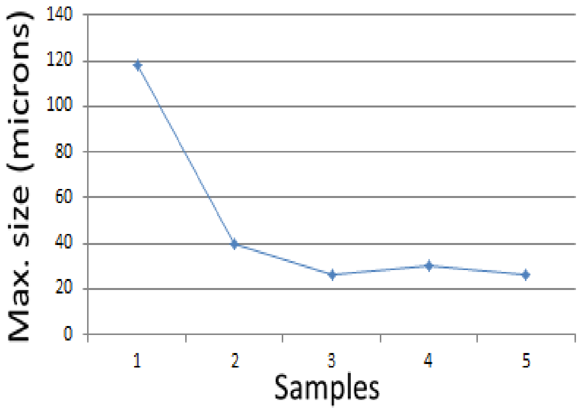

Figure.21: Graph between Max. size of White Non ferrous particle with vehicle run.

White Non Ferrous particles from components (piston, power assembly area, etc.) in sample 1 is found of max. size up to 118 microns this is due sudden impact wear but overall wear rate is found normal in all samples. Presence of white Non Ferrous sliding wear particles could be due to severe sliding stress due to excessive load/speed conditions on the piston and related components which may lead to failure.

Gear wear particles

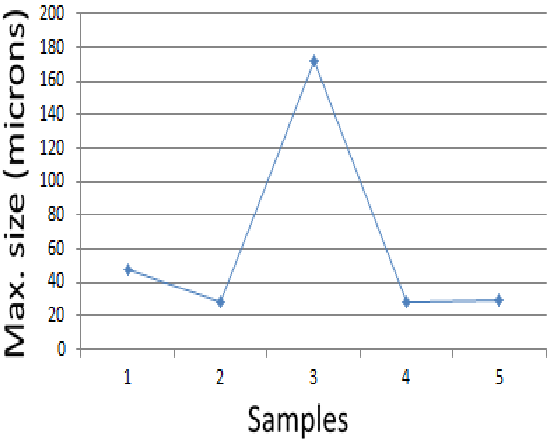

Fig.22 : Graph between Max. size of Gear wear particle with vehicle run.

As In Gear there is sliding and rolling motion takes place . For sliding contact, wear takes place mainly by adhesion and abrasion. However, asperities can make contact without adhering or abrading and can undergo plastic deformation from the contact stresses. As the deformation continues, cracks may nucleate at and under the surface. With subsequent loading and deformation, cracks extend and propagate, finally resulting in wear fragment formation at a critical number of contacts .In sliding contact, the maximum shear stress occurs at the surface, which may lead to surface fatigue. Many rolling contacts are frequently accompanied by sliding and the friction stresses due to sliding cause the maximum shear stresses to be nearer surface fatigue .
As it is shown in fig.22 that the Gear wear particles found normal in all samples but the max. size found in sample 3 is of 172microns, this is due to abnormal operating condition which caused the maximum shear stress occurs at the surface which may lead to wear.

Other contaminants

Other than above particles some particles like copper, sand/dirt, red oxide, black oxide are also found.
Very fine copper particles are observed in some samples and these particles could be from bushing ,washers etc. but was in very small quantity and has no such effect.
Sand/dirt particles observed marginally in initial samples 1 or 2 but in other sample it was in very small quantity.

Initially rating of red/black oxide was marginal during initial run of vehicle but later it observed in small quantity.

7. CONCLUSIONS

The normal rubbing wear particles, severe sliding wear particles, bearing particles, gear wear particles, found in marginal quantity during initial run of vehicles, and it is clear from this the initial wear rate of engine components like piston, piston ring, crankshaft, bearings etc. found was more and their sizes are more than 100 microns which is adverse failure. Large quantities of rubbing wear particles can create excess rubbing of internals and can lead to the generation of secondary wear in the equipment. During initial run of engine or say up to certain distance of engine run cleaning the lubricant (centrifuge to remove the existing wear particles and contaminants) or changing the lubricant is necessary to avoid the generation of secondary wear i.e. abrasive wear.

Presence of white non ferrous sliding wear particles could be due to severe sliding stress due to excessive load/speed conditions on the piston and related components which may lead to failure. Excessive sliding stress on the ferrous components(gears, cams, cam rollers ,etc.) is also indicated by the presence of marginal quantities of low alloy steel sliding wear particles.
From this study Inspection of internals can be planned at the earliest possible maintenance schedule for severe wear out of piston and related components.

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