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Size distribution analysis of wear debris generated in HEMM engine oil for reliability assessment: A statistical approach

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ABSTRACT

Wear debris size distribution in lubricated system closely related to lubricant condition and wear process. In this work, a model has been developed to predict the wear severity with operation time. The used oil samples were collected from Heavy Earth Moving Machines (HEMM) (Model No: BEML BH50M – dumper) employed in open cast mining (Dhanbad, India). Ferrography was used for the isolation as well as capturing image of wear debris from the collected samples. The captured images of wear debris were then processed for the generation of particle distribution using ImageJ software. It has been observed that most of the wear particles are found in 1–25 μm size range. The particle distribution over time has been studied using Weibull distribution model. Based on the statistical modelling of wear particles distribution with time of operation, results show that the percentage of larger particle (>25 μm) increase with time.

1. Introduction

Wear debris analysis is a successful method in industry to examine machines reliability and hence improve it. It has been observed that optical and electron microscopy helps in predictive maintenance before immense failure. It also helps to characterize wear debris and contaminants present in fuel of diesel engines [1]. Wear mechanism and chemical composition has been studied by transmission electron microscopy of wear particles in motor oil [2]. In oil analysis, an optical ferroanalyzer test has been found to be useful to serve real-time wear monitoring for low concentrations (5×10^{-4} mass %) of wear debris [3]. It has been observed from rolling wear tests that the surface morphology of wear debris and parent material has a good correlation, and helps in understanding the wear mechanisms and characteristics [4]. Wear debris analysis was used to monitor the structural integrity in spline coupling. Kurtosis was used to show the variation of wear particle distribution, amount of particle and also recognise the wear damage [5]. A separation method has been applied to improve ferrographic inference in on-line machine condition monitoring [6]. Ken et al. [7] introduced neural networks and expert systems to analyse the wear particles morphology and wear mode respectively. An Integrated package (three-dimensional particle analysis system, an automatic particle identification system and an expert system) has been used for machine condition monitoring and fault diagnosis using wear debris analysis [8]. Manoj et al. [9] summarized that using artificial intelligence method, wear debris can be categorized efficiently without any dependency on human expertise. Support Vector Data Description (SVDD) model was used for automatic identification of wear stage of an engine in real time [10]. It has been found that combination of principal component analysis and grey relation reduces the limitation of ferrography [11]. Logistic regression model has been found to be 89% correct on the classification of oil analysis data for the engines of mining trucks [12]. A new on-line ferrographic analyser was used to evaluate wear debris concentration for certain flow rate and operative time with multilinear regression analysis [13]. On-line visual ferrograph and index of particle coverage area (IPCA) were used to obtain wear debris concentration. A model has been developed between wear debris concentration and wear rate for real-time wear monitoring [14,15]. Ruggiero et al. used three eco-friendly lubricants (Fatty Acid Methyl Ester (RME), Hydrotreated Vegetable Oil (HVO) from raw rapeseed oil and raw Jatropha Curcas L. (JCL) oil) for analysing the wear in ball-on-disk tribometer. Wear debris analysis results show that HVO has the best anti-wear performance as comparison to JCL and RME [16]. Size and number of wear debris have been calculated under sliding wear tests (lubricated condition) using on-line particle counter. The wear amount calculation in real time is found to be suitable to identify abnormal wear [17]. Fan et al. introduced a mathematical model for lubrication system to understand the change in wear debris concentration with wear rate [18].

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Polyethylene wear debris size distribution modelling has been reported for artificial hip joints to understand the wear process involved [19]. Optical particle counter (OPC), aerodynamic particle sizer (APS) and fast mobility particle sizer (FMPS) were used for size distributions analysis of wear particle generated during braking [20]. Wear particle size distribution obtained from ferrograph has been analysed using distribution models. It was observed that interpretation of data using distribution models is a valuable diagnostic tool [21]. Weibull distribution was reported to be more accurate for reliability analysis of lubricants. It also acts as an aid in scheduling oil changes and oil performance evaluation [22]. Statistical analysis based on wear concentration is more effective to estimate engine condition [23]. Very few available literatures have been found analysing wear severity using particles size distributions with time of operation. In the present work, a statistical method is used to estimate system health at any specific time through wear particles size distribution.

2. Methodology

The case study takes in consideration engine oil of a dumper (BEML BH50M). The dumper is used for the coal handling process and this is operated for 16–18 h a day with an intermittent break of 1–2 h after continuous operation of 5–6 h. The collection of oil samples were done from a particular open cast coal mine and under the same loading condition and as well as the same environmental condition during the entire study. The temperature ranges approximately from 40 °C to 48 °C and humidity reaches maximum up to 70%. The capacity of engine lubricant chamber was 250 L and complete draining of lubricant was being done at a frequency of 300 h with filter change also. Four samples were collected on an hourly basis of usage at an interval of 75 h approximately starting form fresh. The sample-1, sample-2, sample-3 and sample-4 are collected at 75, 150, 225 and 300 h of operation respectively. The collection of sample is done by using vacuum pump and storage bottles. The sample collection units are cleaned after every sampling with solvent (heptane) and rinsed with fresh oil. The oil samples are generally, collected immediately after the machine stopped, in order to obtain homogeneity of the oil before the wear debris get settles at bottom of the chamber and water layer get separated if any.

Ferrography is a powerful technique to separate wear debris present in lubricating oil and provide microscopic analysis also [24,25]. In the present study, analytical ferrograph model T2FM is used to separate the wear particles present in samples on a substrate. Fig. 1 shows the ferrograph and bichromatic microscope used in the experiment. The substrate preparation is done in three stages:

i) thinning of samples with solvent (heptane) and perception of wear particle in high gradient magnetic field,
ii) washing residual oil present in slide, and
iii) fixing of wear particle on the slide permanently.

Using bichromatic microscope, image of wear debris present in 6 mm length at entry (i.e. from 56 mm to 50 mm) of the ferrogram are captured along the length to obtain accurate distribution [26].

Microscopic image of substrate at entry position is shown in Fig. 2(a). It shows most of wear debris are present in the strings and connected form. Particles size above 5 μm are taken into consideration for this analysis, as these particles are generated due to rubbing wear [27]. Then the images are processed to obtain wear debris features and to create data base for statistical investigation [28]. The particle features such as major length, minor length, areas and perimeters are analysed using ImageJ [19].

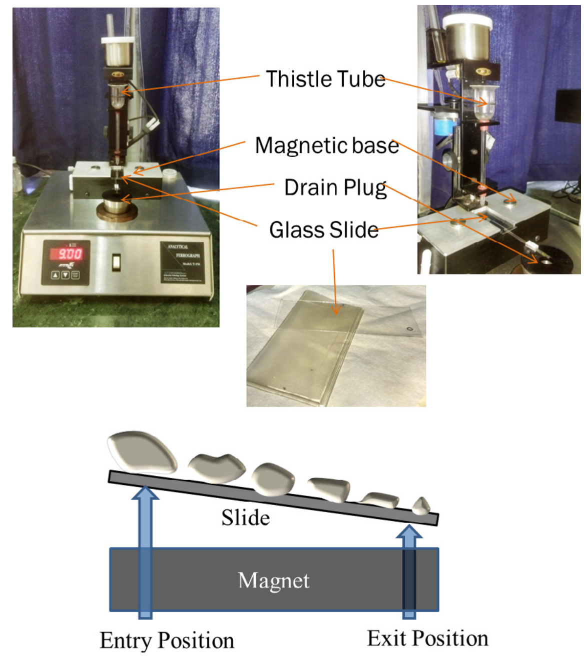

Fig. 1. Details of ferrogram maker.

The flow process of particle features measurement is shown in Fig. 3. The ferrograph image (as shown in Fig. 2(a)) is taken as input to ImageJ for particle features measurement. Initially the scale is set using command "Analyse > Set Scale" for the image calibration. A straight line has been drawn over the scale bar of the image in order to correlate the pixel length to physical measurements as shown in Fig. 2(b). The RGB image is converted to the grayscale image in Fig. 2(c), using command "Image > Type > 8-bit". The image has been thresholded using command "Image > Adjust > Threshold" to get concerned features of particles and related background as shown in Fig. 2(d). In the present study the lower limit varies in between 0 and 255 and upper limit is fixed at maximum of 255 Gy levels. Original and processed images are compared in order to reduce influence from erosion and dilation [29]. Watershed segmentation is used to avoid overlap in the image following the command Process > Binary > Watershed, as shown in Fig. 2(e). "Analyse > Set Measurements" command is used to calculate the required particles features such as area, perimeter, and feret's diameter and the measurements are done by using command "Analyse > Analyse Particles". "Show > Outline" function is opted to display and particles number as shown in Fig. 2(f). The command "Analyse > Measure is used to obtain the result in the required format.

2.1. Distribution functions

Weibull distribution was introduced in 1951 [30]. Presently it has various applications in different fields like material science, engineering, physics, chemistry, meteorology, medicine, pharmacy, economics and business, quality control, biology, geology, and geography [31]. For analysis of wear particle size distribution, a Weibull density function is selected in this study. The Weibull function was chosen over other often used distribution functions because it has wide range of applicability and simplicity for use in modelling particle size distributions [29].

Weibull probability distribution function and cumulative distribution function with two-parameters are expressed as [32–34]:

$$f(x|a,b) = \frac{b}{a}\left(\frac{x}{a}\right)^{b-1}\exp\left\{-\left(\frac{x}{a}\right)^{b}\right\} \quad (1)$$