On-line Ferrous Debris Density monitoring in sliding area contacts under boundary lubrication regime

A.Torres Pérez[a], M.Hadfield[a], S.Austen[b]

a) Sustainable Design Research Centre, Bournemouth University, Fern Barrow, Talbot Campus, Poole, Dorset BH12 5BB, UK
Phone: +44 (0) 1202965079 Fax: +44 (0) 1202965314 Email: atperez@bournemouth.ac.uk
b) Royal National Lifeboat Institution, Poole, UK

Abstract

Tribology experiments with pin on disc configuration are conducted using an oil condition monitoring system. This type of condition monitoring system comprises an oil condition sensor, a moisture sensor and a ferrous debris density sensor based on the principals of Magnetometry.
The experiments are conducted under boundary lubrication regime for two hydraulic oils, reference oils with additives and without additives.
Controlled experimental conditions facilitate the characterisation of the evolution of wear within the sliding pair. The identification of abnormal trends during the wear process indicates the onset of fault conditions. Results show the ferrous density measurements are not directly related to the wear process because of the influence of particles deposition phenomena. Hence, a direct relationship between the real wear volume loss and the ferrous density measures is difficult to establish. Results reveal the speed of particle deposition depends to a high degree on the size of the particles, the oil viscosity and the capacity of stirring. Therefore, the characterisation of the speed of particle deposition is of relevant importance to provide a real indicator of wear progress and thus enable more information for the effective prediction of faults within machinery.

1 Introduction

In situ monitoring of lubricant oil quality and wear debris are important maintenance techniques within military, transportation and manufacturing industries. Costs are potentially reduced as these techniques typically allow the effectively scheduling of maintenance downtime and oil changes. Although frequent oil changes are an effective way to protect machinery they may add an operation expense in terms of unnecessary costs in labour, material and the impact on environmental pollution. Therefore, in most industrial machinery a well-planned maintenance strategy is critical in order to reduce equipment failure rates and costs [1,2].

It is standard practice of lubricant manufacturers to add to the base oil active extreme pressure and/or anti-corrosive additives which tend to inhibit the formation and build-up of contaminant materials. As the machines are operated, the concentration of the additives is depleted to the point where they fail to perform their inhibitory function, thus resulting in important increases in the amount of contaminant material exiting within the lubricant. Furthermore, these additives are organic and organo-metallic chemical compounds which due to the operating environment and conditions of the machines may degrade into acid or basic components. Therefore, the degradation process of lubrication oil is influenced by the accumulation of metal wear particles and other contaminants like mineral acids such as sulphur, nitrogen and hydrohalic based acids, soot and water amongst others. The final result is oil whose acidity, corrosivity and viscosity has substantially increased as it reaches the end of its useful life which can result in disastrous consequences. As a result, it seems reasonable to monitoring the oil quality and wear debris [1]. They offer an important insight into the appropriate time when oil should be changed and also when mechanical repairs might be necessary [2,3].

The analysis of oil can be performed in-line, on-line or off-line [2]. Off-line analysis allows an accurate characterisation of the sample but it has the drawback of analysing misrepresentative samples. Real time oil monitoring is based on in-line and on-line analysis. Real time results are not as detailed and accurate as off-line results but they reduce the problem of misrepresentative samples.

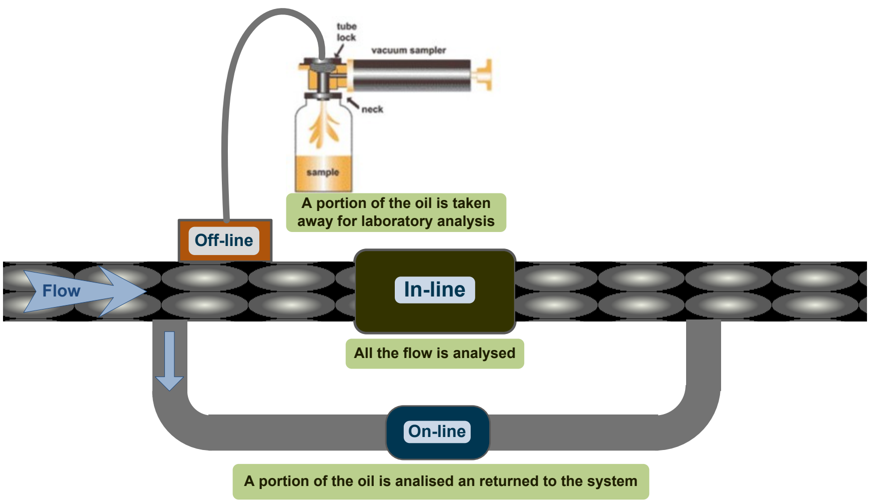


Fig 1. Typical connection types for oil sampling and analysis

This research evaluates on-line ferrous density monitoring from a tribological point of view. Experimental results will provide the reader with an assessment of the influence of the particle deposition process in the ferrous debris measurements. Conclusions are presented based upon the results shown.

2 Experimental Methodology

2.1 Experimental Test Rig

The type of commercial oil condition monitoring system used is the Online Sensor Suite manufactured by Kittiwake Developments Ltd. This suite comprises three sensors, a metallic ferrous debris sensor an oil condition sensor and a moisture sensor. A picture of the system is shown in Fig 3a.

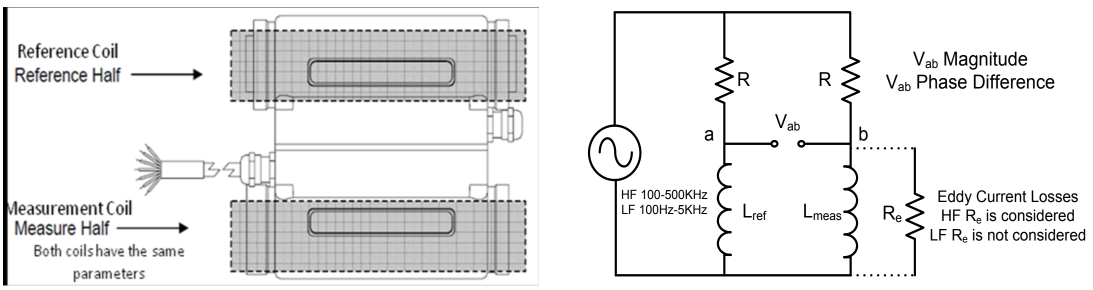
This study is based on results obtained using the ferrous debris sensor. The sensor was selected among others because it relies on the principals of Magnetometry and it is based on two fundamental physical effects [4]:

- The change of inductance due to the presence of a magnetic material (changes in permeability).
- The change of energy losses due to electromagnetic induction in any conductive material (Eddy currents losses).

The changes of permeability and the losses due to eddy currents are measured by means of two symmetrical measurement chambers: measure and reference halves as shown in Fig 2. The reference half remains empty, while the other chamber is filled with the fluid sample [5]. The sensor measures the difference between the halves. As a result, its output is a signal proportional ferrous debris density. The sensor provides the ferrous density by weight (ppm = g/m^3 or mg/dm^3 or mg/l).

This method of sensing is independent of the particle size. The sensor has a repeatability of 5ppm if the different of temperature between halves is less than 10ºC. The volume of the oil inside the sensing chamber is approximately 40ml.

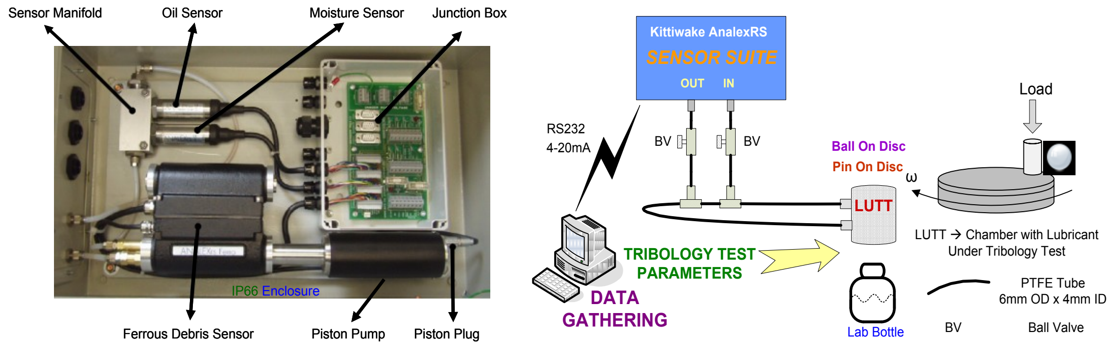
The sensor is connected to a PLINT TE92HS rotary tribometer Fig 3b. The used oil is stored to characterise the deposition of ferrous debris particles under different temperatures. Oil temperature is controlled by a heater block underneath the lubricant bath. Accurate regulation of temperature during the experiment is possible with a K-type thermocouple and PID control.



a) Chambers and coil location

b) Basic signal conditioning circuit

Fig 2. Layout of Ferrous Debris Sensor and supposed signal conditioning circuit



a) AnalexRS Sensor Suite b) Schematic diagram

Fig 3. Experimental Set-up

2.2 Test Methodology

There are different methods for selecting a specific bench test according to experience, standardized test, or limitation in available equipment. The Tribological Aspect Number (TAN) was developed to assist the test designer in making the transition from the field problem to bench test [6]. However, when the goal is the characterisation of the output of real time sensors, the selection of the bench test is constrained by the inherent limitations of the sensors. The most important parameters to be taken into account are the sensitivity and repeatability. The sensitivity of the sensor implies a limitation in typical tribological test configurations. For the ferrous debris sensor, the sensitivity is 1ppm but it should be borne in mind that 1 ppm for an oil chamber of 40ml corresponds to a total weight of ferrous debris of 40μg. The sensor has a repeatability of 5ppm thus the minimum discernible mass is 200μg. This wear mass is equivalent to a wear volume loss in steel (density of steel is 7850kg/m3) of 0.025478 mm^3. This amount is above the typical wear volumes in concentrated contact experiments. Preliminary for the ball on-disc configuration confirm this.

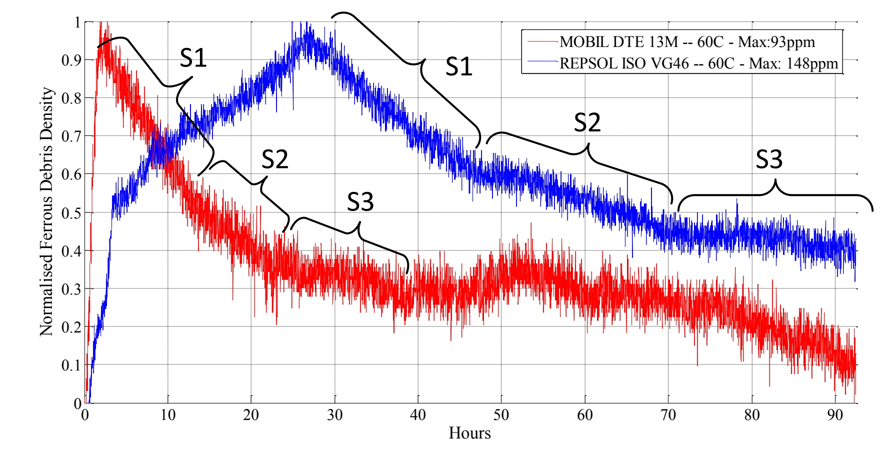
As result, a line or area contact is the best option to achieve wear rates measurable by the sensor. Therefore, the selected type of test is pin-on-disc. The disc is EN24T steel hardened to 500-550HV and surface finish less than 0.2μm while the pin is mild steel 150-200HV with a surface finish of 5μm. Within this tribological pair severe wear in the pin is expected. Tests were developed under fully flooded oil conditions at 60ºC (typical operating temperature of hydraulic machinery), normal load of 300N (this corresponds to mean contact pressure assuming an ideal flat surface of 5.97MPa) and a spindle speed of 100rpm (contact speed is 0.2618m/s as the distance from the center of the pin to spindle centre is 2.5cm). Two types of oils are considered: a pure mineral oil without additives of grade ISO VG46 provided by REPSOL and a commercial additivised hydraulic oil ESSO MOBIL DTE 13M of grade ISO VG32. The quantity of oil per test is 125ml and it is pumped with a flow rate of 40ml/min.

The contact area is operating outside the visco-elastic range so there are only two possibilities: there is a lubricant film separating the mating surfaces or not. The pin is machined with a flat profile without chamfer in order to avoid a converging wedge inlet which can generate a lubricant film. The reading of high values of coefficient of friction ensures that the experiment is running in boundary lubrication regime. Several parameters are collected during the test: the applied load, the speed, the temperature, the coefficient of friction and the ferrous debris density.

3 Results and Discussion

Ferrous debris density measurements for the two reference oils are shown in Fig 4 with an approximate value of friction coefficient is shown in Table 1. During the running-in process the coefficient of friction decreases until it stabilises. At this point, the waviness and roughness of the two contact surfaces are similar with a high degree of conformity.

The comparison of ferrous density results is evaluated by means of normalizing the ferrous debris density using the peak value. As it is expected the wear is less when the lubricant has an additive package. Important trends are highlighted in Fig 4.



Mobil DTE 13M	Repsol
Initial Pin Weight	Initial Pin Weight
7.8117g	7.6021g
Final Pin Weight	Final Pin Weight
7.8022g	7.5905g

Fig 4. Normalised ferrous debris density

Table 1. Coefficient of friction

	0 min	15 min	30min	45min	60min	90min	120min	48hrs
Repsol	0.08	0.08	0.08	0.08	0.07	0.05	0.04	0.01
Mobil DTE 13M	0.08	0.07	0.04	0.04	0.04	0.04	0.04	0.01

The evolution of wear is shown in Fig 5. This graph is obtained by doing experiments with the same pin running 12 repetitions at regular intervals of 10min. The pin was properly aligned to same position before each test. Fig 5 is especially helpful to identify the matching degree of sensor response and the real wear in the tribological pair. A visual representation of roughness evolution of the pin is shown in Fig 6. As it is shown in Fig 5, after 2 hours the wear is almost stabilised. The sensor predicts this effect with a delay of almost 30min. After the wear is stabilised, the influence of the particle deposition process plays an important role. The generated wear is negligible comparing to the effect of particle deposition phenomena thus the ferrous debris density trend drops quickly. From Fig 4 different slopes are easily identified. Each slope corresponds to a different range of particle sizes. Small particles are in suspension for a longer time than large ones. The type of particles is measured using ferrographic techniques [3,7,8]. The particles are trapped in a glass specimen using a variable magnetic field. Different particle sizes and cluster of particles are shown in Fig 7.

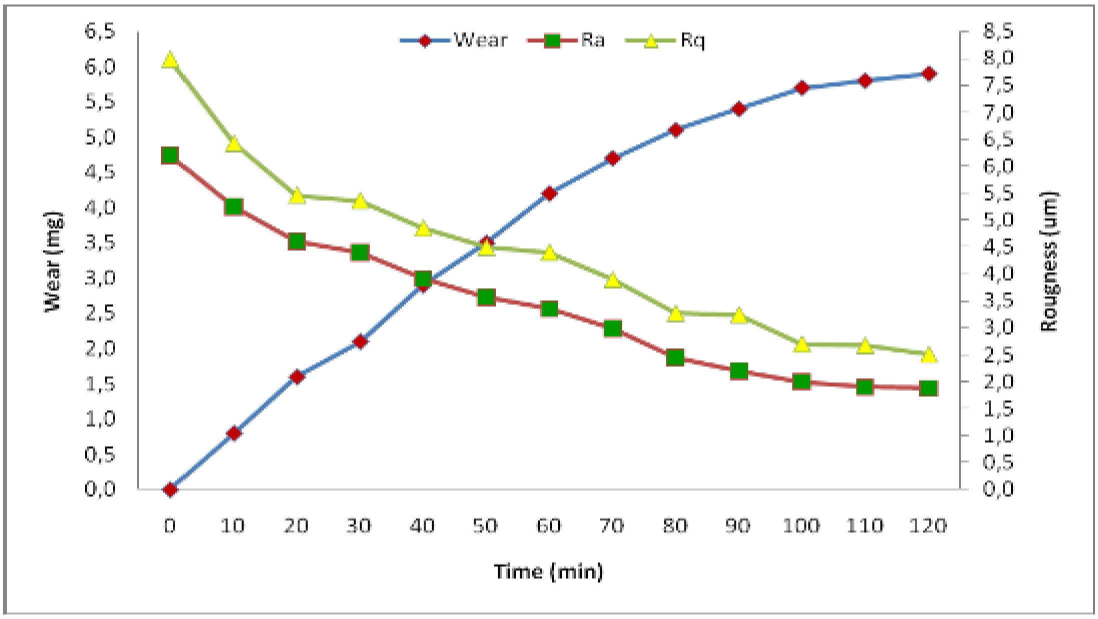


Fig 5. Evolution of wear and roughness of pin counterface (Mobil DTE 13M)

Table 2. Roughness evolution of the pin. The lubricant is Mobil DTE 13M

Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)
0	7.7983	50	7.7948	100	7.7926
10	7.7975	60	7.7941	110	7.7925
20	7.7967	70	7.7936	120	7.7924
30	7.7962	80	7.7932		
40	7.7954	90	7.7929		

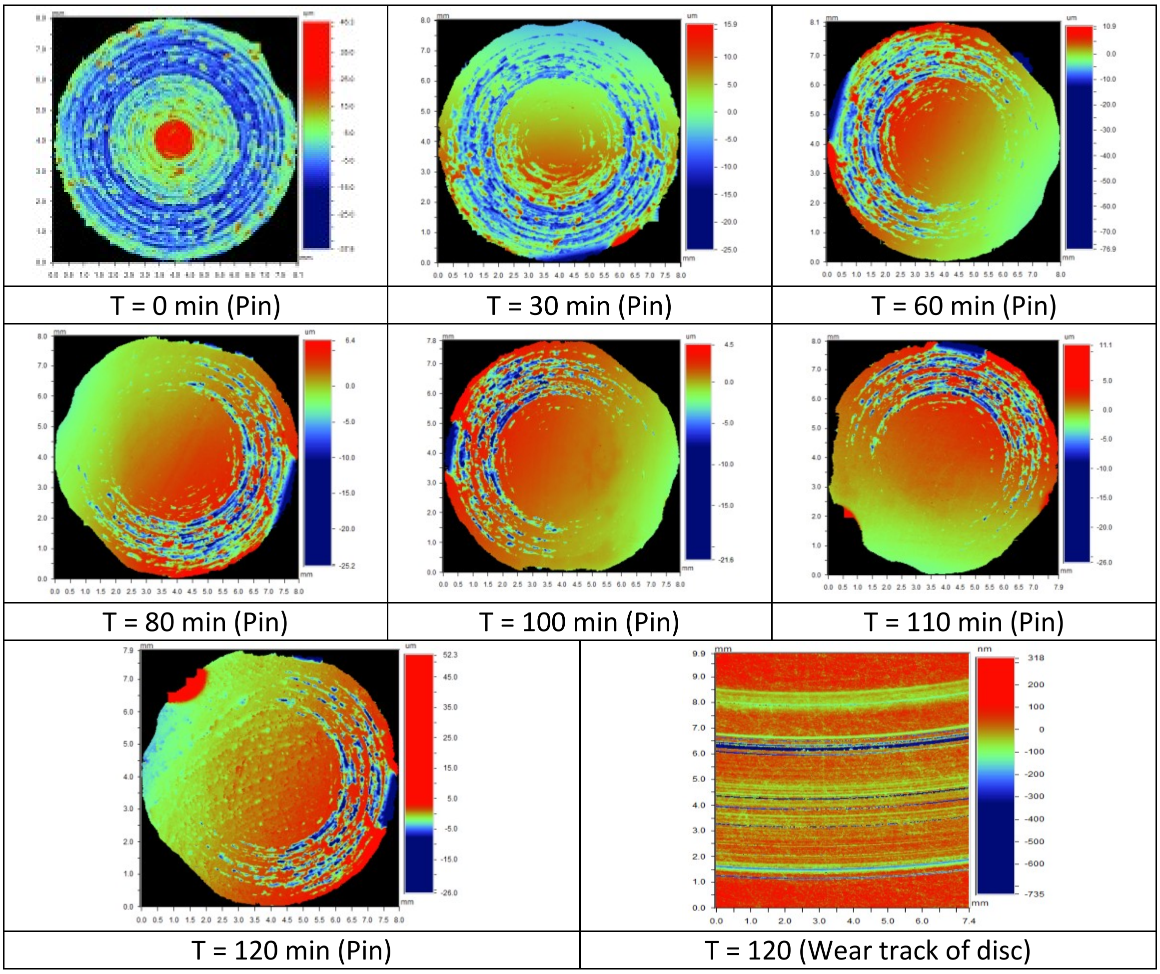


Fig 6. Topographical images of the evolution of wear

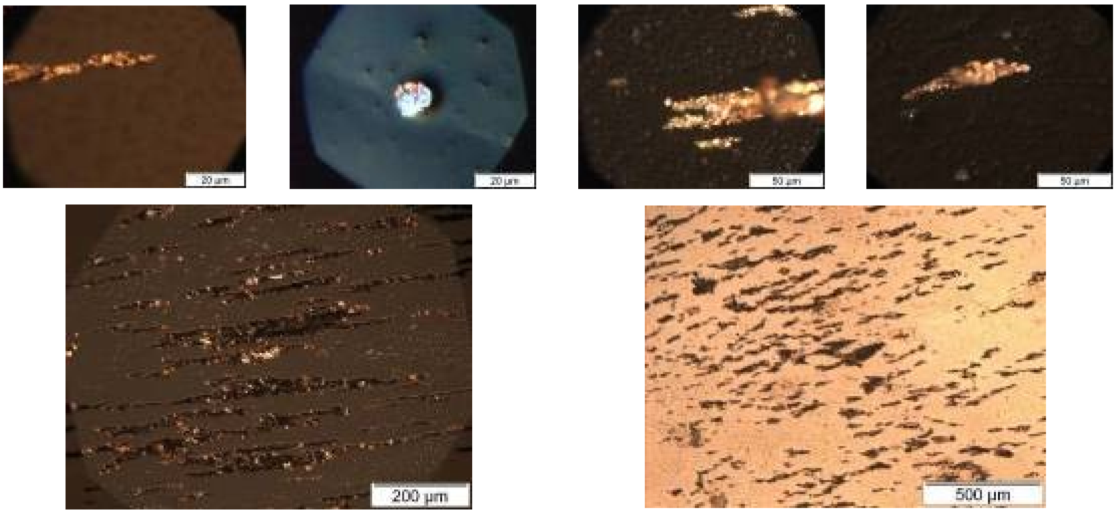
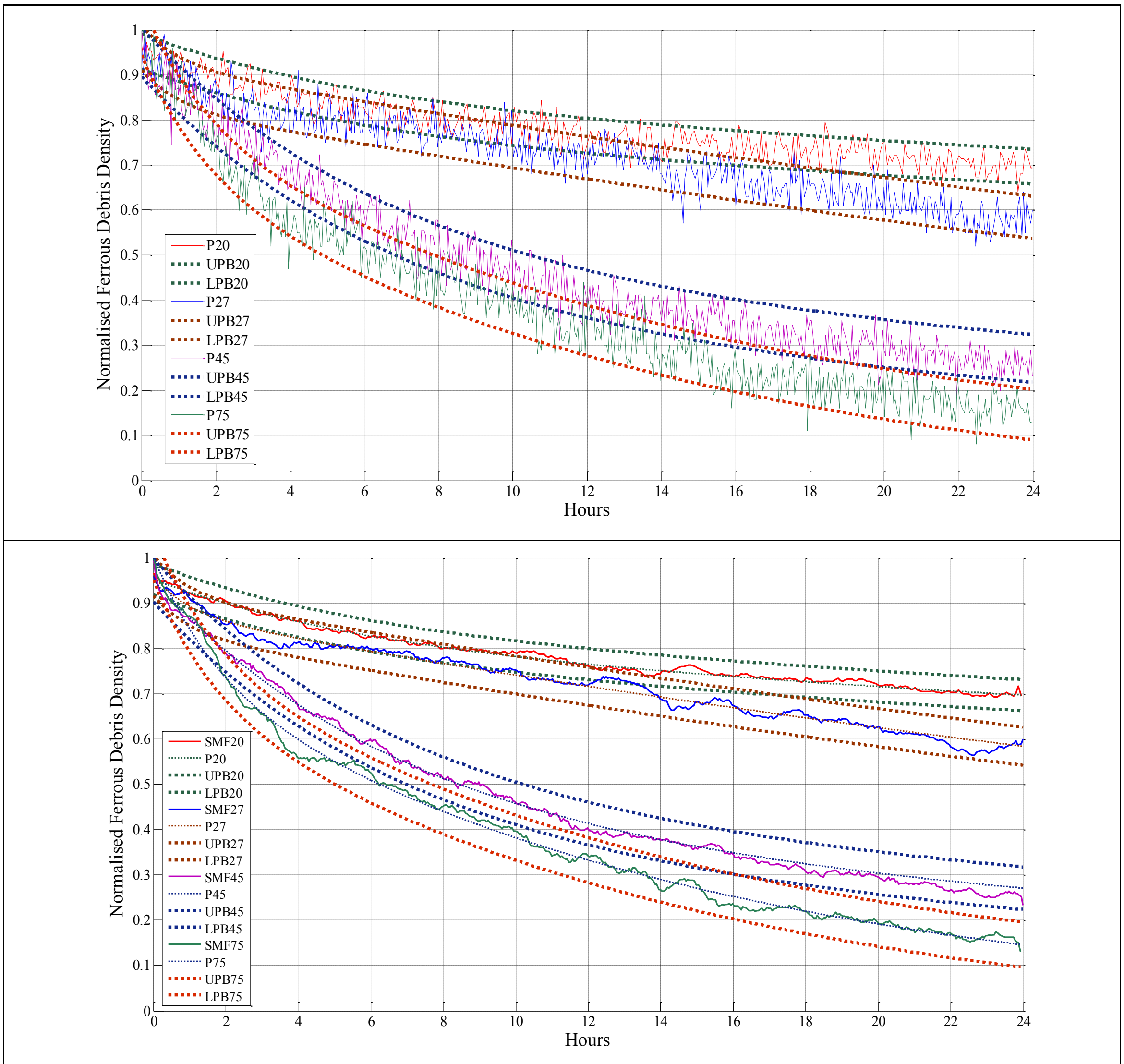


Fig 7. Ferrogram analyses of used oil.

The characterisation of temperature influence within the particle deposition process is done storing the used oil in a bottle. Before taking any measurement the lubricant is stirred and the temperature is stabilised using a hot-plate. Obtained results of the normalised ferrous debris density are shown in Fig 8. A non-linear regression model based on two exponential functions fits the data with a high degree of accuracy. The parameters of the model are shown in Table 2.

Oil viscosity decreases as temperature increases. As a result, when the temperature increases, particles sink more quickly.



P → best prediction of proposed model SMF → Smoothing of data by moving average filter	UPB /LPB → upper / lower prediction bounds for the 80% of confidence level

Fig 8. Deposition of ferrous debris at different temperatures

Table 3. Prediction model parameters

	Temp: 20ºC	Temp: 27ºC	Temp: 45ºC	Temp: 75ºC
Maximum Values (ppm)	147 ppm	102 ppm	93 ppm	100 ppm
	Proposed regression model for the normalised data $f(x) = ae^{bx} + ce^{dx}$			
Temp: 20 ºC	a = 0.1519	b = -0.1696	c = 0.8005	d = -0.00593
Temp: 27 ºC	a = 0.0829	b = -1.0390	c = 0.8788	d = -0.01703
Temp: 45 ºC	a = 0.5368	b = -0.1509	c = 0.4142	d = -0.01996
Temp: 75 ºC	a = 0.2439	b = -0.5979	c = 0.7595	d = -0.06879

4 Conclusions

The experimental results confirm that ferrous debris density monitoring can be a late indicator of the incipient fault detection depending on the particle deposition process. It should be considered that the on-line detection of ferrous debris density has an inherent lag depending on the sampling point. Although this lag affects the response time in the fault detection process it can be determined if the flow and pipe distance from the sensor are known.

The effectiveness of ferrous debris density measurements depends on the uniform suspension of the debris. Therefore, this monitoring technique is reliable in systems with small sumps and rapid circulation of the lubricating oils. Examples of these systems are reciprocating engines, power train components and aviation turbine applications. If this monitoring technique is applied to machinery with stationary lubrication oils and large sumps the effective fault detection cannot be guaranteed. An extreme case of misrepresentative results may arise when machinery operates under start-stop conditions with low utilisation factor. In this case, the incipient fault detection using ferrous debris density measurements can be only achieved if the particle deposition process can be determined within machinery.

The experimental results reveal that particle deposition is a complex physical phenomena mainly dependent on temperature, particle size, oil viscosity and the capacity of stirring the oil. Therefore, modelling the particle deposition process in real machinery implies a significant challenge.

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