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Current trends in ICE wear detection technologies: from lab to field

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Abstract

Research in internal combustion engine (ICE) tribology has been an active topic during the last decades, driven by different interest: first, in order to improve thermodynamics and overall engine performance, while nowadays there is an interest in reducing engine losses, including friction, in order to cut down fuel consumption and also exhaust emissions.

Tribology is a tri-vector science, where friction is the fundamental phenomena occurring between two surfaces, wear is the consequence of the occurrence of friction and lubrication is the solution for diminish friction and eliminate wear presence in the tribological system.

During the development of ICE, different technologies and techniques have been applied for detection of ICE wear, focused in different parts of the engine life and also used for different purposes, including research or maintenance.

In this work, a comprehensive look on this field is done, where several techniques are explained and their main application and pros and cons are highlighted.

Keywords: ICE, wear detection techniques

1 Introduction

The development of internal combustion engines (ICE) has considerably evolved in the last decades as emission legislation has become increasingly strict worldwide. With fines to be paid for too high emission levels, the pressure on the automotive OEMS has never been higher to produce more and more efficient engines. This motivation has led to the development of a number of measures to decrease fuel consumption of which may cause considerably higher stresses for specific parts of the engine. After all reducing friction power losses in the engine directly translates to increased fuel efficiency and is, therefore, highly attractive. New developments in this field include:

New engine operation modes and constructions

One of the most widely used possibilities to improve fuel economy especially for inner city driving, is the employment of start-stop systems Bishop, J., et. Al (2007) and Silva, C. et. al (2009). By switching off the engine instead of idling it inefficiently during waiting times at crossings etc., significant fuel savings can be obtained Silva, C. et. al and Fonseca, N., et. al.(2011) More recently, this procedure was even extended to shut down the engine also during driving for very low loads, which is commonly called engine coasting. These systems have quickly become widely available, but despite their apparent simplicity, the repeated stopping and starting of the engine still can be a source of problems. The reason for this is that during this stopping and starting procedure the journal bearings experience mixed lubrication as their lubrication follows the entire Stribeck-curve Sander, D. E.,et. al (2016).

New ultralow viscosity lubricants

The usage of low viscosity lubricants in the automotive sector is certainly not new. Increasingly strict legislation forces the automotive industry to increase the engine efficiency and few ways to achieve this are as economic as the usage of a lower viscosity lubricant, which is considered to be a very effective measure for the whole industry Holmberg, K., et. al (2014). However, the current trend goes to lubricants with drastically reduced viscosities and new standards had to be defined accordingly Covitch, M.,et. al (2010). With the new SAE standards 0W16 M.,et. al (2010). and even lower classes being targeted, pure hydrodynamic lubrication conditions will more and more diminish and be replaced by mixed lubrication near the EHD minimum Sander, D. E., (2015), Knauder, C., et.al (2015) and Ligier, J. L.and Noel, B.,(2015).

Aggressive downsizing

Both in terms of combustion as well as concerning engine friction, higher loads mean higher efficiency as the thermal and mechanical losses scale only weakly with the higher load Allmaier, H., et.al (2012). This trend has led to the development of engines with drastically higher power-to-displacement ratios within less than 20 years. To give a specific example: in Europe, a sporty, turbocharged 1.8 liter Gasoline engine from 1999 produced 65kW per liter displacement, while in 2015 a sporty, turbocharged 2.0 liter Gasoline engine operated up to 130kW/liter. As the geometrical dimensions of the piston, conrod etc. remained about the same and the weight of the parts even slightly decreased, twice the original power is obtained from new engines. This trend still continues and engines with an even higher power-to-displacement ratio are announced. At the same time the approved lubricants for these new engines are of considerably lower viscosity than were used in 1999, which together with the doubled mechanical loads promotes mixed lubrication.

The Stribeck-curve shows that the friction minimum lies in the mixed lubrication regime and indeed many measures to reduce internal engine friction (as was discussed previously) lead to increased metal-metal contact. While the use of coatings increases and also modern lubricants involve state-of-the-art additive chemistry to withstand this increased metal-metal contact, the risk of increased wear and reduced lifetime is still present and needs to be assessed experimentally.

2 Engine wear detection techniques

During the development of internal combustion engines, the study of wear has been a highly developed area of interest mainly related to durability and maintenance purposes. On the other hand, alternatives are necessary where wear can be detected in early stages of engine usage.

In last decades, many different approaches have been applied for the detection of engine wear, in both qualitative and quantitative ways. There are several aspects that need to be taken into account in order to select between different measurement techniques. Firstly, the expected materials and size of the wear debris generated could reduce the range of solutions available. Also, the generation rate and amount of wear will influence the selection of measurement method. The main division between techniques performed in this paper has been done related to the nature of the research performed. In a research facility, it is compulsory to perform precisely measurement, to detect the smallest differences in research parameters or the materials involved. In contrast, if a field study is being conducted with longer periods and greater amounts of wear, a simpler technique with less precisions could be used P. J. Blau, (1992).

2.1 Wear research

In the majority of mechanical systems, typical wear processes occur immediately, but a great part of their effects occur over a long scale time, usually after hundreds of hours of operation. However, in engine tribology research this approach is not desirable, since speed and accuracy are highly desirable test qualities, as most of the test developed for lubricant homologation in Europe lasts around hundreds of hours (CEC, (2016)). Traditional wear measurement techniques in this area present many disadvantages. As an example, there is a high difficulty to detect transient wear in specific points, since in traditional methods it is necessary to disassemble and measure part dimensions and weight in order to detect wear variations. In order to get additional test performed, a reassembly of engine is demanded, and this could modify wear processes and conditions. Different wear measurement technologies have been developed that can avoid these problems, making them interesting for research purposes.

2.1.1 Radioactive nucleoids methods

The application of radioactive techniques to measure wear is not recent, since gamma-ray detection principle has been widely used during the last decades to measure wear in engines and for lubrication testing (C. C. Blatchley, (1992)). This approach presents a range of advantages: it provides on-line in-situ readings of wear production and rate, both effectively and in real time, and can offer precision in the range of μg.

In this technique, the main physical principle is the detection of irradiated wear debris from selected parts from the engine and collected by lubricant by means of a gamma ray detector. A diagram of the test bench is shown in Figure 1.

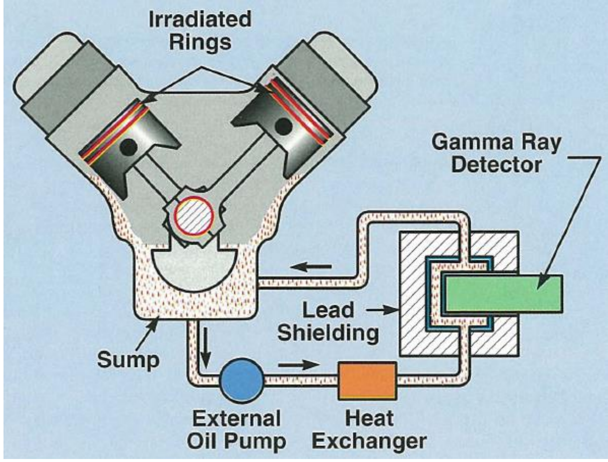

Figure 1. Diagram of an engine equipped for radioactive wear measurements. Adapted from (M. B. Treuhaft and D. C. Eberle (2007)).

Prior to the test, it is necessary to “activate” the particular wear surface in order to detect the specific wear debris coming from this surface, since they emit gamma rays that allow monitoring the wear process during test. In this approach, a particle accelerator is used to produce a thin layer of radiotracers at the surface of wear parts. When wear processes take place, debris is released to the lubricant. After that, radioactivity in the lubricant is measured and wear presence can be quantified in an exact way.

This technique permits wear measuring under real-time conditions in operating ICE and other mechanical systems. In addition, the ability to measure tiny variations of wear debris allows evaluation of wear in a large matrix of ICE operating conditions and studies of wear kinetics. The capability to perform on-line wear measurements on running engines without dismantling parts is also convenient for real-time wear measurement on research tribological materials.

Several research groups have been using this technique, mainly applied to study effects of different engine improvements (M. B. Treuhaft and D. C. Eberle (2007), P. Carden, et. al (2013), M. Scherge, et.al (2003), E. Corniani, et. al (2009), A. Gauthier and T. Delvigne, (2000) and A. J. Dennis, et. al (1999)), but the test cost reduces its spread in engine tribology research.

2.1.2 Online Visual Ferrography (OLVF)

Another technique developed for short-term wear detection is known with the acronym OLVF (Online Visual Ferrography). Analytical ferrography is considered a key technique in machine condition monitoring and fault diagnosis in mechanical systems. However, traditional measurements are performed off-line in specialized laboratories because of complex operation, and this makes this test time consuming and costly. In the continuous development of new wear detection techniques, an evolution of ferrography has appeared. Y. Liu, et. al (1992), (1997) and (2000) developed an on-line ferrograph using a long deposition distance with a high intensity magnetic field and six photoelectric sensors, where wear debris larger than 5 μm could be detected. Different developments during the last decade made this device evolve to an on-line visual ferrograph (OLVF) T. H. Wu,(2009).

This device works as follows: oil from the mechanical system is derived into a transparent flow channel where a magnetic and optic system is installed. In this situation, wear debris is trapped in this channel and can be visualized by means of the optical system. In a diagram of the system is shown.

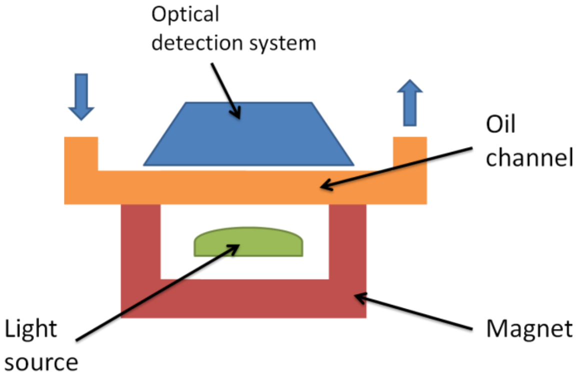

Figure 2. Diagram of an OLVF. Adapted from T. H. Wu,(2009).

This device has been used for testing premature wear in gasoline engine test bench Y. Zhang,(2011). In this case, this device detected presence of ferromagnetic particles larger than 5 μm and they could make a distinction between small and large particles. In this test, they detected abnormal wear patterns in an earlier stage than other techniques used. In conclusion, OLVF could be used as a tool in on-line wear monitoring, capable of detecting wear changing trends instantaneously.

2.2 Engine condition monitoring

On the other hand, several options have been developed from the maintenance sector as condition monitoring techniques in order to detect the tribological status of mechanical equipment C. Evans, (1978). These techniques are characterized for their wide implementation in industry, robustness and development, and they use lubricating oil as test fluid.

These techniques can be divided in several groups depending on some properties: For example, some of them identify the presence and quantities of various metallic elements present in the lubricant, while other detect failures by analyzing the quantity, sizes, and images of wear debris. Also, they can be performed on-line or off-line, and each technique has a limitation in types and sizes of wear that can be detected.

2.2.1 Wear in used oil analysis

Used oil analysis as a maintenance tool for different mechanical systems is used since the mid-twentieth century. After WWII, oil analysis appeared within the railway maintenance sector to control engine performance. Gradually, an expansion process was carried out into other fields of application such as transmissions, gearboxes and gas turbines, among others. The breakthrough of these techniques came from the aeronautical field, transport fleet and military maintenance, where it is generally known as JOAP (Joint Oil Analysis Program). Thanks to the development done, oil analysis has become an essential tool to perform predictive maintenance in ICE C. Evans,(1994) , and also to detect engine wear.

2.2.1.1 Atomic emission spectrometry: ICP-OES and RDE-OES.

Spectrometry is a technique for detecting and quantifying the presence of elements in a material. Each element emits light of specific wavelengths when subjected to the addition of energy, and the intensity of the emitted light is proportional to the quantity of the element present in the sample. Depending on the energy source, two different techniques have been applied for ICE wear detection.

2.2.1.1.1 ICP-OES

ICP-OES (Inductively Coupled Plasma – Optical Emission Spectrometry) is a technology widely used in the present for oil analysis, and it is present in ASTM D5185 standard for its application on lubricating oils.

This technique is based in the use of argon plasma as an excitation source for the engine oil. Plasma is a state of matter, defined as a gaseous mixture containing electrically conductive significant concentration of cations and electrons. Temperatures reached inside of the plasma can get up to 10000 K. A diagram of the system is presented in Figure 3.

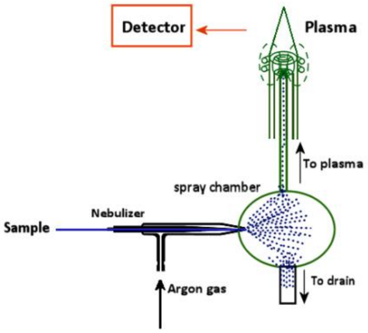

Figure 3. Diagram of ICP-OES technique.

Although this technique presents a series of great advantages (high temperatures, repeatability, stability, low detection limits), its major drawback is the particle size. ICP-OES detection efficiency varies depending on the particle size particles that are dissolved in the oil ASTM International, (2005). After 5 µm of mean particle size, the detection efficiency drops until 20 µm, where ICP-OES is not capable to detect these particles.

2.2.1.1.2 RDE-OES

Another method used as an excitation source applied to lubricating engine oils is the application of an electric arc discharged to the sample creating a high temperature zone which vaporizes a portion of the sample forming the plasma Spectro Scientific Inc., (2014). The oil is added to the plasma through a graphite disc system, which gets the oil in the plasma due to rotation. In this process local plasma reaches temperature in the range of 5000-6000K. This technique is referenced in the standard ASTM D6595, and a diagram is shown in Figure 4.

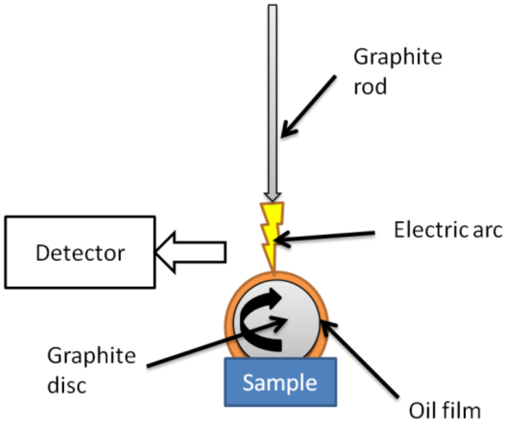

Figure 4. Diagram of RDE-OES technique.

In comparison to ICP-OES, this technique presents a lower plasma temperature, resulting in higher detection limits. In addition, a fresh disc is required for each sample to eliminate sample carryover. On the other hand, RDE-OES is a robust technique that can be used by non-experimented people, and there is no need from external chemicals.

2.2.1.2 XRF

XRF (X-ray fluorescence) technique identifies and quantifies the chemical elements in a sample, and can be used in both off-line and on-line systems. The sample is irradiated with X rays that act as a excitation source. When the electrons return to their original state, they emit X rays in an energy level associated with the particular element, and the intensity is proportional to the concentration of the element.

2.2.1.3 Laser particle counting and classification

This equipment, known as LaserNet Fines Spectro Scientific Inc., (2014), analyses particles in a fluid by image processing based on laser to directly characterize the size and number of particles. This equipment is capable of counting particles greater than 4 µm and classifying particles larger than 20 µm by shape to predict engine wear: cutting, sliding, fatigue, nonmetallic, fibers or water droplets.

2.2.1.4 Ferrography

Ferrography is a well-known technique for wear monitoring in mechanical equipment. In ferrographic oil analysis the magnetic separation of ferrous wear debris is done by means of an oriented magnetic field. The particles are arranged in the ferrogram according to size for subsequent examination; unwanted dirt particles are eliminated since they are non-magnetic. A scheme of the ferrography principle and a typical ferrogram is shown in Figure 5.

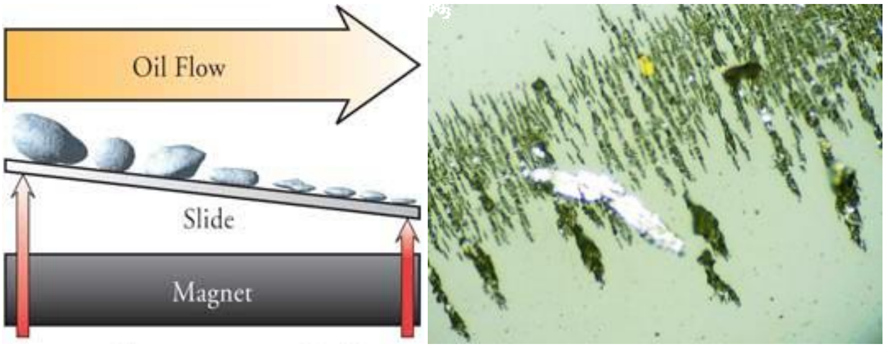

Figure 5. Ferrographic principle (left) and example of ferrogram (right).

After the ferrogram is obtained, it is possible to observe different types of wear debris particles and sizes, which can explain different wear processes occurring in the mechanical system. There are several publications related with the diagnosis through ferrography L. Montoro, (2005) and M. H. Jones, (1983).

2.2.2 On-line sensors

During last decades, a lot of efforts from the maintenance sector have been devoted to the development of on-line sensors for condition monitoring of a wide variety of mechanical equipment, in order to create a synergistic approach with on-line monitoring for routine control and off-line analysis to detect root causes and perform a complete analysis P. G. Adriani, et. al

(2014). There are a whole series of different devices the presence of wear particles in the lubricant T. M. Hunt, Ed., (1993), based on different principles:

- Dielectric Constant: The dielectric constant is a physical characteristic that measures the rate of electric flux density produced in a material by specific electric field strength. This technique is able to detect when a change has occurred in the lubricant. The presence of wear particles alters this dielectric constant, but also degradation processes. Another similar parameter is the dielectric loss factor (sometimes known as Tan Delta), which increases with strongly polar contaminants such as degradation products and metal particles.
- Magnetic flux: With this technique, the concentration of ferromagnetic particles is estimated by a fixed magnetic field. Collected wear particles modify magnetic flux and this variation is detected by a sensor. The change in magnetic flux is converted into the concentration of ferromagnetic particles by means of an algorithm.
- Magnetic pickup: With this technology, the ferromagnetic particles are attracted to a power grid or plates used as opposing electrodes. The current flow between the electrodes indicates the presence and overall concentration of magnetic conductive particles. Depending on the design, these sensors can be used to estimate the particle size and concentration in the lubricant.
- Induction sensors: Magnetic induction is a physical phenomenon in which the magnetic flux is modified if perturbations in the form of particles enter the magnetic field. Typically, an induction coil is placed around a pipe to create a magnetic field through which the fluid passes. By using electronic circuits, it is possible to eliminate air bubbles signal and differentiate between ferrous and nonferrous particles.
- Optical Counters: An on-line particle counting principle is developed in two different ways. In the first case, there is a light beam perpendicular to the fluid, where the particles pass through the detection cell and create a shadow behind the fluid. This causes a voltage drop, proportional to the size of the shadow, so it can be detected and quantified. For the second case, the light scattering is virtually zero until it passes a particle beam. When the beam hits a particle, light is scattered and reaches the photodetector. This produces a voltage change associated with the particle size. Usually, this second group is more accurate than the first. However, both types of sensor have problems inlet air bubbles and water drops, which produce reading errors.
- Counters for pore blockage: Like optical counters, they have the advantage of measuring only solid particles, so that the presence of air or water in the fluid does not alter the measurement. However, their main drawback is that they need periodic cleaning.

3 Conclusions

In this paper, current development trends in automotive engines and the consequent motivation to study wear were presented. An overview of current trends in ICE wear detection technologies has been given, covering different applications and purposes. The main conclusion is that currently a wide variety of techniques exist that offer different characteristics, strengths and weaknesses. Unfortunately, no single particle analysis technique is completely satisfactory in providing both qualitative and quantitative data. Also, while research techniques and some lab analysis like ferrography offer concise and interesting information, they are expensive and time consuming. On the other hand, on-line techniques present immediate and cost-effective data, but it is obtained in limited quantity or quality.

This leads to the following conclusion: is it necessary to understand the purposes and necessities of the research performed in order to apply the most suitable wear detection technique or combinations of them, so it is feasible to maximize the data collected and the adequacy of it.

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