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Use of Various Tribo-Analytical Tools for monitoring the Lubricant used in Industrial Applications

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Introduction;
Tribology is the science and engineering of interacting surfaces in relative motion. It is the study of lubrication, friction and wear when two surfaces are in relative motion. Tribology has enormous practical importance to industrial maintenance because it not only optimizes functionality of lubricants between the two mating surfaces but also helps prolong the life of mechanical equipment/machineries by reducing friction and wear.

I*ndustrial lubrication practices* bring together a broad coverage of the different surface materials, types of lubricants and various techniques employed in tribology for effective lubrication, thereby reducing friction and wear.

It is highly interdisciplinary, drawing on many academic fields including physics, chemistry, materials,surface science, mathematics, biology and engineering. Subfields of today's tribology includes bio-tribology, nanotribology and space tribology. It is also related to other areas such as the coupling of corrosion and tribology in tribo-corrosion and the contact mechanics of how surfaces in contact deform.

Approximately 20% of the total energy expenditure of the world is due to the impact of friction and wear in the transportation, manufacturing, power generation and its distribution and residential sectors.

Tribo-analytical techniques involve multidisciplinary methods used to study the interactions of surfaces in relative motion, focusing on **friction, wear, and lubrication**.

Modern industrial practices involve changes in metal surface and its elemental composition study and its characterisation for any chemical changes after sliding/rotational action between metal surfaces and monitoring the interface lubricant chemical changes by various spectroscopic techniques [1,2,3,4].

KEYWORDS: Interactions of surfaces in relative motion, focusing on **friction, wear, and lubrication**.

Study of Metal Surface and its chemical characterization:
It relies mainly on surface-sensitive techniques to understand the complex processes at the sliding / rotating interface such as the formation of protective **tribo films.**

I. Microstructural Analysis:

Tools such as **Scanning Electron Microscopy (SEM)**, **Transmission Electron Microscopy (TEM)** and Atomic Force Microscopy (AFM) are used to examine wear scars, surface morphologies, and subsurface deformations at high resolution. Metal specimens before and after use are examined and compared for the changes due to deformation on the surface [5].

II. Spectroscopic Techniques for metal Surface:

X-ray Photoelectron Spectroscopy (XPS) and **Auger Electron Spectroscopy (AES)** identify changes in chemical – elemental as well as formed organo-metallic compositions and oxidation states of elements on the surface. Metal specimens before and after use are examined and compared for the changes due to composition on the surface after deformation [6].

All the above surface tribo-techniques are very useful and very informative to know the surface morphology including wear patterns and fatigues mechanism. The instruments are very expansive and may not be readily available in majority of Industrial & R & D laboratories and needs analysis to be outsourced.

III. Tribo- Analytical Tools such as Vibration meter and Thermography (Heat/ temperature sensing) on the machinery is mostly commonly used in industry [7, 8].
Sound and noise are physical observations which also helps for detecting some problems with the machinery. Most representative and reliable tool is Vibration Meter.

A) Vibration Meter:

Machines/Equipment exhibit a characteristic, non-anomalous smooth (acceptable) vibration “signature”. Acceptable vibration is based not only on the type of equipment but also operating conditions and even environmental variables such as temperature or humidity. When an anomaly in machine operation occurs, the vibration signature changes. The change in vibration signature can capture majority of failure modes in a machine (particularly rotating machines) and can thus be used to diagnose problems. ISO 10816/20816 describes the standards to be adopted for failure mode diagnostics using vibration information [9].

Some of the most common machinery problems that cause vibration include:
Misalignment of couplings, bearings and gears, unbalance of rotating components, looseness, deterioration of rolling-element bearings, gear wear, rubbing, aerodynamic/hydraulic problems in fans, blowers and pumps, electrical problems (unbalance magnetic forces) in motors, resonance, eccentricity of rotating components such as “V” belt pulleys or gears.

Measurement Parameter	Fresh Machine (Baseline)	Runned Machine (Degraded / Worn)	Primary Engineering Indicator
Overall Velocity (RMS)	**Low** (e.g., 0.5 – 2.0 mm/s)	**High** (e.g., 4.5 – 11.0+ mm/s)	Structural health, unbalance, misalignment
Acceleration (Peak/RMS)	**Minimal** (e.g., < 0.2 g)	**Elevated** (e.g., > 1.5 g)	High-frequency bearing defects, gear mesh wear
Displacement (Peak-to-Peak)	**Negligible** (e.g., < 15 µm)	**Significant** (e.g., > 50 µm)	Low-frequency issues, structural looseness, sleeve bearing clearances

Table 1 Typical Vibration Data Comparison (Motor)

Figure 1: Vibration Meter

B) Thermography:

A thermography test, or thermal imaging, uses infrared cameras to detect invisible heat emissions from objects, identifying potential faults, insulation failures, or hot spots in electrical/mechanical equipment before failure. This non-destructive, cost effective, non-contact testing method is critical for preventive maintenance, enhancing safety, reducing energy loss, and avoiding system downtime [10,11]

Figure 2: Thermograph on Electrical Panel

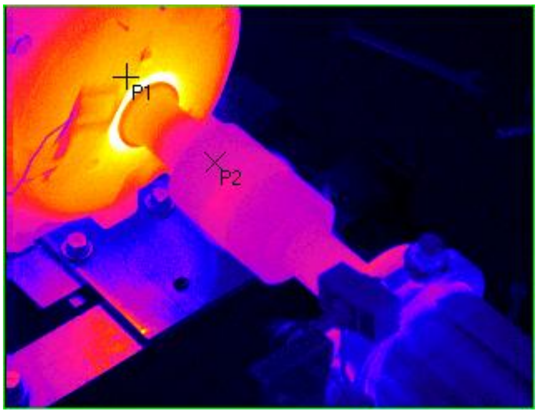

Figure 3: Running machine showing heat Zones images

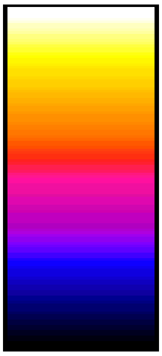

Figure 4: Color Codes

VI. Tribo analytical tools for monitoring lubricant used for lubrication:

Monitoring the lubricant in laboratories is most commonly practiced in both industrial and automotive applications. Tools used are affordable and less expansive. The information obtained from the lubricant analysis are very conclusive and reproducible. The important change observed in lubricant after usage is the molecular compositional changes of the lubricant due to oxidation, depletion of performance additives in the lubricant and any new compound formed if any [12,13].

Techniques such as **Raman Spectroscopy** and **Fourier-Transform Infrared (FTIR) Spectroscopy** allow researchers to observe chemical changes and lubricant behaviour in real-time during the friction process. Details of the usefulness of instruments are covered under Raman Spectrometer and FTIR Spectrometer [14,15]

a) Raman Spectrometer:

Itprovides non-destructive, real-time molecular data lubricant composition, oxidation, and additive degradation. Evaluating structural changes in lubricants and greases, specifically tracking oxidation and saturation **(ratio of 1655 to 1440 bands) under high temperature and load.** Additive Analysis: Identifying the presence and degradation of additives including solid lubricants in grease. Distinguishing between different lubricant types (synthetic vs. mineral) and identifying potential contamination into lubricant can be performed.

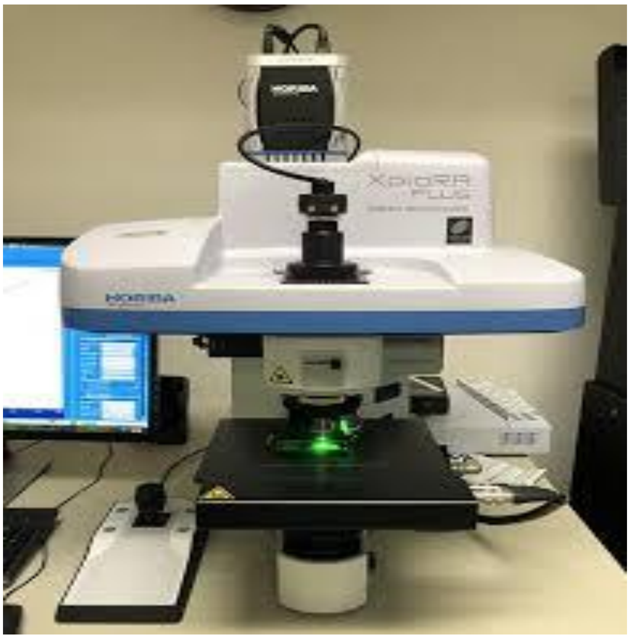

Figure 5: Raman Spectrometer

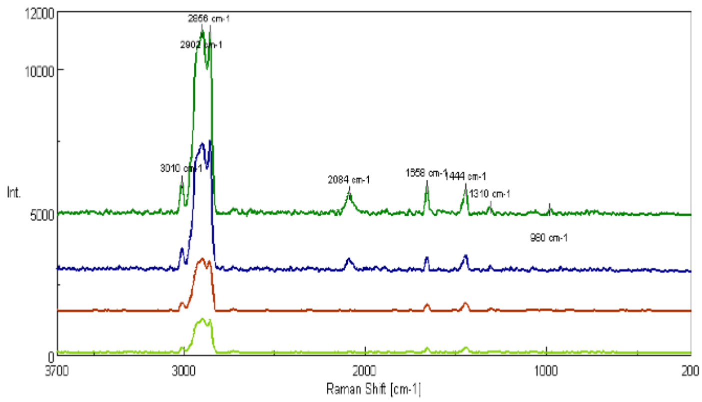

Figure 6: Spectral Range 3000cm-1 to 200cm-1 Raman Spectrum of Lithium Grease at different Load Condition Fresh Grease (Light Green) Load IN ,5N and 10 N

b) Fourier-Transform Infrared (FTIR) Spectrometer:

Fourier Transform Infrared (FTIR) spectroscopy is a very informative and non-destructive analytical technique. It is widely adopted as tribological tool in research activities pertaining to Lubricant. The technique is used effectively to analyze the chemical composition of lubricants, surfaces, and tribo-films, particularly for studying degradation pattern and wear mechanisms. It provides molecular-level information by analyzing how materials absorb infrared light, acting as a "fingerprint" to identify functional groups, contaminants, and additives.

Advantages of FTIR in Tribology: Fast and Accurate: Provides quick, detailed insight into complex mixtures (lubricant + additives + contaminants). Small sample Volume: Requires minimal sample 0.5 ml to 1ml, essential for testing with limited amounts of debris or lubricant. Non-destructive: Allows for subsequent testing of the same sample. In-situ capability: Attenuated Total Reflection (ATR/FT-IR) tribometry enables the analysis of chemical changes during sliding between surfaces.

Figure 7: FTIR Spectrometer

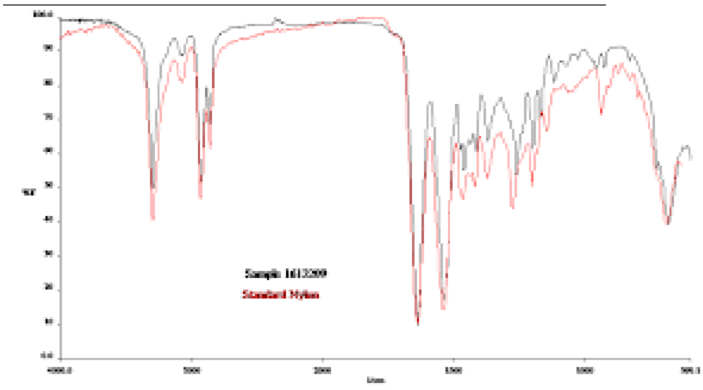

Figure 8: FTIR Spectral comparison (Overlay)

Secondly, by monitoring wear metal particles (elemental) generated from the machinery equipment parts into lubricants gives important information on wear nature of machinery parts, its level and pattern. Above information can be obtained in-situ by drawing lubricant sample by stopping the machinery momentarily or drawing the lubricant sample after periodic run intervals recommended by OEM.

Three most commonly used tribo-analytical techniques used for elemental composition as well as for wear metal debris analysis are **Atomic Absorption Spectrometry (AAS), Inductively Coupled Plasma Optical Emission Spectrometry (ICPOES) and X-Ray Florescence Spectrometry (XRF).** Most of the lubricant testing laboratories are well equipped with either one or more of these instrument facilities. Each technique has its own advantages and sensitivity

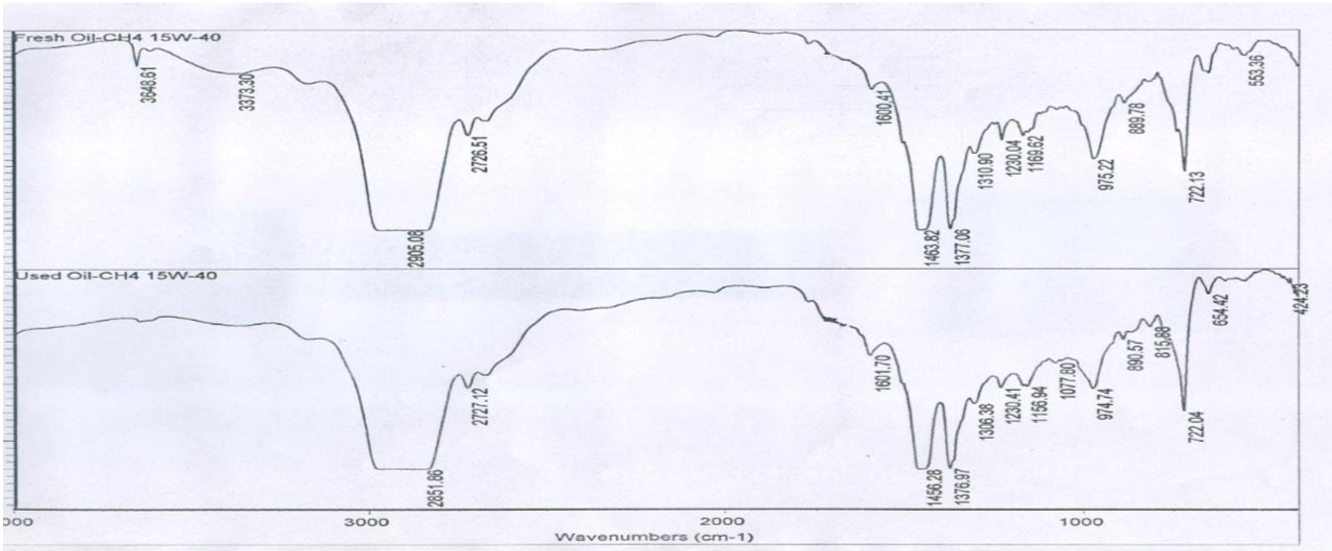

Figure 9: FTIR Spectral (Stack) Comparison of Fresh Engine oil against Used oil

c) Atomic Absorption Spectrometer (AAS):

It is sensitive upto ppm level analysis and is sequential one element at a time, however, involves time consuming sample preparation procedure. The technique is good for qualitative and quantitative analysis of metallic elements only and not sensitive to non-metallic elements such as phosphorus, boron, sulphur which are part of compounds used in lubricants formulations.

Figure 9: Atomic Absorption Spectrometer (AAS)

d) Inductively Coupled Plasma Optical Emission Spectrometer (ICPOES):

It is a powerful analytical technique used to detect and quantify trace elements (metals and some non-metals in ppm to ppt) in liquid or solid samples by utilising a high-temperature argon plasma (7,000–10,000 K) to excite atoms, which then emit light at characteristic wavelengths of elements under study. It has capability which allows for the **simultaneous**, rapid analysis of multiple elements (up to 40) in a single sample with high sensitivity and low detection limits (typically levels). It is widely used analytical technique in lubricant testing for multi-element analysis, primarily for used oil analysis. It measures wear metals, contaminants, and additives at parts-per-million (ppm) level, enabling condition monitoring of lubricants. Besides, it is compliance with International Standard for testing like ASTM D5185, which covers the determination of additive elements, wear metals, and contaminants in unused and used lubricants. It also covers Additive packages analysis used in lubricants including greases. Both destructive and non-destructive sample preparation procedures can be used with solvent dilution. Unlike AAS instrument, ICPOES Instrument is relatively expensive but in recent years many of Indian lubricant and testing laboratories are equipping with this highly sensitive instruments

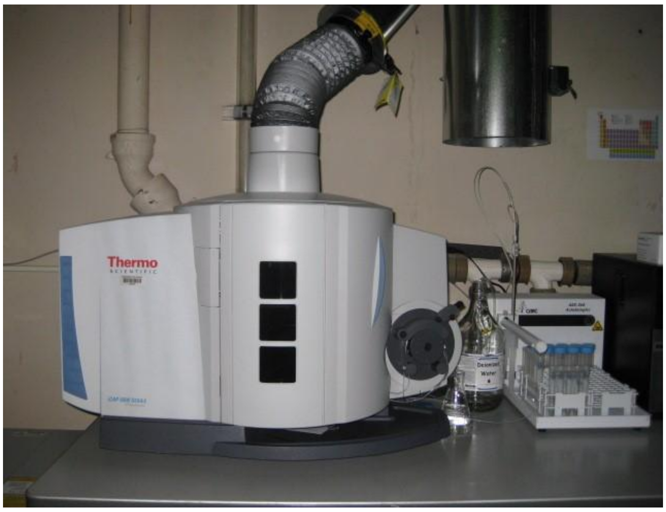

Figure 10: Inductively Coupled Plasma Optical Emission Spectrometer (ICPOES)

e) X-Ray Florescence Spectrometer (XRF):

It is a non-destructive analytical technique used to determine the elemental composition of materials, such as solids, liquids, or powders, by measuring a primary X-ray source. **It qualitatively** identifies and quantifies elements (typically from sodium to uranium) present in a sample. **It is used in** mining, metallurgy, cement, lubricant, petrochemical, and environmental applications. **Methodology:** The process involves firing X-rays at a sample, which causes inner-shell electrons from elements constituting sample to be ejected and subsequent, characteristic secondary X-rays characteristic of elements are emitted and detected. The two main types of instruments are Energy Dispersive X-ray Fluorescence (**EDXRF**) and Wavelength Dispersive X-ray Fluorescence (**WDXRF**) are available to users.

It is generally rapid, non-destructive, for simultaneous analysis and requires minimal sample preparation. WD XRF instrument is very expensive, but EDXRF is relatively much cheaper instrument and on-site with handheld instrument are also available user.

XRF are critical for lubricant testing, offering fast elemental analysis to measure additive levels, identify contaminants, and monitor metal wear debris. XRF is non -destructive, ideal for measuring additive elements and sulfur in lubricating oil with minimal sample preparation. It is commonly used for detecting elements in wear metal generated from machinery. Compliance with Standards: Meeting international regulations like ASTM D 4294, ASTM D7751 and ASTM D 6443.

Figure 11: X-Ray Florescence Spectrometer (EDXRF)

In addition, other information on physico-chemical analysis of used lubricants are also monitored for evaluating the performance of lubricant. Comparative data collected from both fresh and used lubricant on any of the commonly available associated test rigs for friction and wear, load bearing properties such as SRV Tester, Pin on Disc Wear Tester, Four Ball EP Tester, Reichart Tester, Falex Lubricity Tester will help in monitoring overall lubricant behaviour and its performance [16,17].

Conclusions:

Tribo-analytical Techniques extremely useful for surface and topography analysis of metal lubricant interface surface, compositional changes due to wear of metal surface by chemical analysis, lubricant and wear debris analysis using both analytical and test rigs in the laboratories. Consolidation of all above useful Tribo-Analytical collected data can be used to predict wear level, friction, and optimize lubricant performance. This also gives valuable guidance to the users for suitability of lubricant through its performance or failure.

Future Development:

Regular data collection of the lubricants for OEM suggested Machineries is recommended. This data can be the basis for the development of Artificial Neural Network (ANN) which will help in advance prediction of behaviour of machinery as well as Lubricant (Tribo-informatics). Based on the ANN, development of Artificial Intelligence (AI) for authentic behaviour pattern of both lubricant as well as for machinery can be conducted. More Technological development of very reliable Test Rigs to reduce the gap between data collected from Field samples and LaboratoryTest Rigs should be carried out.

More inter-disciplinary interactions and collaborations between groups will improve understanding Tribology – Friction, Wear and Surface.

Technical Knowledge gap between Academy and Industry needs to be reduced to produce effective improvement through collaborative work with experts from different disciplines and thereby advancement of tribological science.

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