

Original Article

Vibration and Acoustic Emission Diagnostics for Identifying Nano-Additive Effects under Particulate Contamination in Rolling Bearings

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Abstract - This study improves and endorses Vibration and Acoustic Emission (AE) based diagnostic methods to assess the in-service performance of nano-additives in mineral oil-lubricated rolling bearings under solid contamination. Tests were performed using base oil and three nano-additives, namely Tungsten Disulfide (WS_2), Graphene Nanoplatelets (GNP), and Al_2O_3 , under quartz particulate ingress. High-frequency AE and accelerometer vibration signals were recorded with friction, temperature, and wear measurements. Time- and frequency-domain features, including RMS, spectral band energies, AE counts, and hit energy, were extracted and examined and compared to the contaminated base oil, WS_2 and GNP formulations reduced vibration RMS by approximately 33% and 26%, respectively, while AE RMS values decreased by nearly 40% and 32%. Correspondingly, the wear rate was reduced by 65% for WS_2 and 55% for GNP. AE counts and peak energies provided indicators of incipient abrasive events. Envelope and spectral analyses revealed frequency signatures associated with third-body impacts and tribo-film sliding. Correlation analysis confirmed strong relationships ($r > 0.8$) between vibration and RMS, AE RMS, envelope peak amplitude and wear rate. Random Forest classification demonstrated that a subset of AE and vibration features could discriminate the responses of the tested lubricant conditions, particularly the film-forming WS_2 and GNP formulations from the Al_2O_3 condition. Surface analyses using SEM, XPS, and Raman spectroscopy confirmed tribo-film formation for WS_2 and GNP and severe ploughing for Al_2O_3 . The diagnostic framework offers monitoring of lubricant additive efficacy in industrial bearings.

Keywords - Vibration Diagnostics, Acoustic Emission, Nano-Additives, Tribofilm, Bearing Contamination, Wear Monitoring.

1. Introduction

In engineering transmission systems, the rolling bearings are considered as the critical machine elements, whose significant operational reliability staunchly impacts the enactment, energy competence and service life of rotational machineries in a most practical way. In modern as well as in conventional engineering industrial circumstances, bearings are predominantly exposed to antagonistic operating environments, out of which solid particle contagion have been seen as one of the most unfavourable. Further, the hard particle, which originates from the environmental ingress, lubricant degradation, seal leakage or element wear, could enter as the lubricant film and induce third-body abrasion, micro-cutting, notch and surface exhaustion. Additionally, even the slight amounts of contaminants moderately accelerate the advancement of surface damage, unsettle film stability and upsurge frictional heating, which eventually leads to untimely bearing failure [1, 2].

Moreover, several studies relevant to this have emphasized that soiled lubrication lessens bearing life by more than 50% comparative to clean conditions, underlining the need for operational mitigation and observing strategies. In recent decades, the approaches of combination of nano-additives into lubricants have emerged as a promising methodology to increase lubrication performance and resist contamination-induced wear. Nano-additives, including layered sulfides, graphene-based materials and metal/metal-oxide nanoparticles, have been widely investigated for their ability to modify interfacial interactions, promote protective films and reduce friction and wear [3-5]. Surprisingly, the so-called additives unveil various mechanisms such as rolling effect, mending effect, polishing effect, and tribo-chemical film formation, which significantly contribute to lowering wear than mixed and boundary lubrication regimes. However, their behaviour in the presence of abrasive pollutants is not permanently predictable. Lamellar WS_2 and graphene-based



additives can reduce friction and wear through low-shear and transfer-film mechanisms, although the response of any additive depends strongly on concentration, dispersion, counterface and operating environment [6-8].

In our preceding work, the mechanistic interactions between nano-additives and solid contaminants in rolling bearings were investigated. The findings showed that WS₂ and GNP promoted the formation of protective tribofilms and reduced wear, whereas Al₂O₃ exhibited antagonistic behaviour and intensified abrasive action in the presence of quartz particles [9]. These findings provide a mechanistic basis for the present study and highlight the need for real-time diagnostic tools capable of monitoring nano-additive performance during operation rather than relying solely on post-test surface analysis.

Concurrently, old-styled condition monitoring systems are completely relying and dominant on vibration analysis, which was comprehensively used to distinguish bearing faults such as outward race spalling, internal race faults and rolling portion damage. Even though vibration-based features such as RMS, kurtosis and spectral band energies are exclusively worthwhile for recognising enlightened failure stages, which are looked to be less sensitive to refine tribological transitions happening at the premature stages of abrasive wear or tribofilm formation. Such early changes can occur at micro-scale levels, motivating the complementary use of high-frequency sensing alongside conventional vibration monitoring [10].

Acoustic Emission (AE) monitoring has significantly gained consideration for noticing minuscule events that head to macroscopic bearing damage. Correspondingly, AE devices are proficient in apprehending high-frequency stress waves spawned during severity interactions, crack initiation, material deformation and particle collisions. Likewise, AE features such as counts, energy, hit rate and peak amplitude have been revealed to deliver premature warning indicators in unclean lubrication and during the abrasive wear scenarios [11]. When united, vibration and AE form a dominant hybrid investigative framework that could be apprehended in both macro-scale dynamic responses and micro-scale tribological events. Irrespective of the possibility of untowardness on vibration and acoustic emission-based approaches, so far, only a few restricted examinations have been tried to methodically correlate these signal features with the tribological presentation of nano-additives under unclean lubrication conditions.

In most of the current studies, the so-called vibration and AE analyses are treated as the independent variable, from the chemical and mechanical mechanisms governing additive behaviour, which results in fragmented analyses. Subsequently, the relationships between protective tribo-film formation by lamellar and carbon-based additives such as WS₂

and GNP, the abrasive connections prompted by solid impurities and hard ceramic additives like Al₂O₃, and the instantaneous diagnostic signs apprehended complete vibration and acoustic emission monitoring remain poorly stated. Addressing this gap requires an integrated framework linking tribological mechanisms with multi-sensor condition indicators, consistent with the broader condition-based monitoring philosophy [12].

To address this gap, the present study develops an integrated diagnostic framework that combines high-frequency acoustic emission, broadband vibration measurements, time-frequency analysis, and signal-based feature extraction to evaluate nano-additive performance under particulate-contaminated lubrication. The study extends the tribological analysis by linking dynamic signal responses with wear behaviour and post-test surface characterization. The novelty of the present work lies in the combined interpretation of vibration, acoustic emission, wear response, and surface characteristics to distinguish protective film-forming behaviour from abrasive interactions during contaminated lubrication.

The main contributions of this study are as follows:

- Integrated multi-sensor diagnostic framework: High-frequency AE, broadband vibration, time-frequency analysis, and signal-based features are combined to evaluate nano-additive performance under particulate-contaminated lubrication.
- Quantitative linkage between signals and tribological behaviour: The study establishes relationships between vibration RMS, AE RMS, envelope characteristics, wear rate, and the formation of protective tribofilms for WS₂ and GNP, as well as abrasive behaviour associated with Al₂O₃.
- Early diagnostic identification of additive behaviour: AE counts, high-frequency spectral components, envelope features, and vibration responses are used together with wear and surface characterization to identify changes associated with tribofilm formation and abrasive interactions.
- Machine-learning-based classification: A Random Forest classifier is applied to distinguish the responses of the film-forming additives (WS₂ and GNP) from the abrasive Al₂O₃ condition, providing an additional condition-monitoring perspective [13].

The remainder of this paper is organized as follows. Section 2 describes the materials, experimental setup, lubricant formulations, contamination conditions, and data acquisition procedures. Section 3 presents and discusses the vibration, acoustic emission, frequency-domain, correlation, statistical, classification, and surface characterization results. Finally, Section 4 summarizes the main findings and conclusions of the study.

2. Materials and Methods

Figure 1 represents the schematic representation of the experimental analysis depicted in this particular study. Actually, the bearing test rig consists of a bearing test, a loading arrangement with a lubrication circuit, along with the sensor placements in various locations to monitor the vibration and acoustic emission measurements. Besides, accelerometer and AE sensors were positioned in the exact locations of the rig to capture the sensitivity in the rolling contact events as well as in particle-induced transients. Furthermore, the schematic representation also reveals the test sequences that were followed in all experiments, which successively ensure the reproducibility of the methodology.

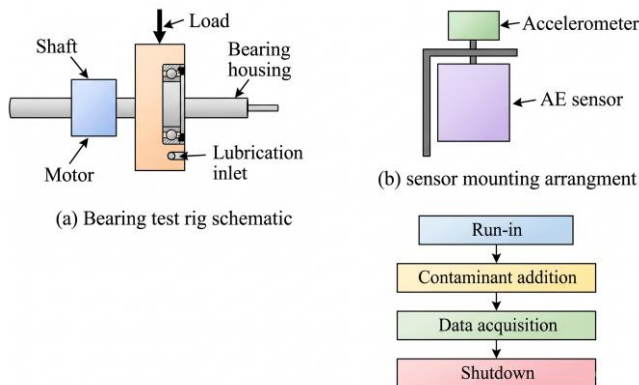


Fig. 1 Overview of the experimental setup and procedure.

2.1. Lubricant Formulations and Nano-Additives

To do the analysis, four lubricant systems were prepared for this approach. In that sequel, the commercially available ISO VG 68 mineral oil was successively utilized as the base fluid, which was having the viscosity of 68 cSt at 40°C and 8.5 cSt at 100°C. Also, three sets of nano-additive formulations were initiated by successively dispersing the nano-particulates tungsten disulfide (WS_2), Graphene Nanoplatelets (GNP) and Aluminium Oxide (Al_2O_3) into the base oil. The WS_2 nanoparticles with 40-80 nm were added at the level of 0.1 wt.% to evaluate their lamellar-film lubrication response; WS_2 nanosheets are well established as low-shear lubricant additives [7].

Along with this, GNPs with the lateral sizes of 1.2 μm and thicknesses of 5–10 nm were greatly dispersed at the rate of 0.05 wt.% to explore the carbonaceous film-forming tendencies. Furthermore, Al_2O_3 nanoparticles with 50 nm, which are familiar for their abrasive nature, were also further introduced at 0.1 wt.% to act as an antagonistic reference. All meticulously prepared formulations were stirred with a magnetic stirrer and also successively monitored through the ultrasonication to confirm uniform dispersion in order to avoid agglomeration. Additionally, fresh samples were prepared then and there, before testing, in order to avoid sedimentation. Probe ultrasonication was carried out using a 20 kHz ultrasonic processor with a maximum power rating of 750 W,

operated at 40% amplitude for 30 minutes in pulse mode (10 s ON / 5 s OFF) to ensure homogeneous dispersion of nano-additives. The importance of stable nanoparticle dispersion in lubricating oils has been emphasized in the literature [14].

2.2. Contaminant Characteristics and Preparation

Similarly, in order to prevalent the exactness of the study, quartz particles were selected since it possesses high hardness and frequent presence in the industrial dust as contaminants. The chosen particles were in the size range of 25-45 μm and were completely dried by treating them at a temperature of 60°C prior to use in order to consecutively eliminate moisture [1, 2]. Besides, 0.1 wt.% of concentration was further blended into each lubricant formulation, and continuous stirring was done to ensure uniform suspension. The chosen concentrations were preferred based on the preliminary screening experimental analysis, which indicated observable vibration and AE responses without further inducing immediate bearing failure.

2.3. Bearing Test Rig and Operating Conditions

The dynamic behaviour of the system under the circumstances of contaminated lubrication was evaluated with the help of the custom-built rolling bearing test rig. The chosen test bearing was a standard deep groove ball bearing with a specification of 6204 series, which was driven at a constant rotational speed of 1600 rpm. Correspondingly, a radial load of 3.0 kN was successively applied by using the hydraulic loading mechanism.

As well, lubrication was constantly supplied through the recirculation oil bath retained at $33 \pm 2^\circ C$, by maintaining an inlet flow rate of 0.4 L/min. Moreover, to conduct the experimental sequences, each experimental run lasted for 60 minutes; also, each procedure was repeated three times to confirm the exactness. Besides, friction torque was captured by using an in-line torque transducer, while lubricant temperature was continuously monitored by using a PT100 sensor.

2.4. Vibration Measurement and Signal Acquisition

Apart from that, vibration measurements were successfully obtained by using the stud-mounted ICP accelerometer with a sensitivity of 100 mV/g. Further, sensors were fixed on the bearing housing in the radial direction to capture localized dynamic responses associated with rolling contact. Similarly, the vibration signals were experimented with at 25 kHz by using an NI cDAQ-based data acquisition system. In the same way, both the time-domain and frequency-domain features were positively taken out, which include RMS, crest factor, peak amplitude, skewness, kurtosis, dominant frequencies and band-limited spectral energies. Envelope analysis using the Hilbert transform was employed to detect bearing characteristic frequencies such as BPFO, BPFI, BSF and FTF, following established rolling-bearing diagnostic practice [10, 15].

2.5. Acoustic Emission Measurement Setup

High-frequency acoustic emission signals were recorded using a wideband AE sensor with a frequency response from 100 kHz to 1 MHz. The sensor was mounted on the bearing housing using a high-vacuum coupling agent and a steel band clamp. A 40-dB preamplifier was used to enhance signal levels, and a high-speed digitizer with a sampling frequency of 2 MHz captured the AE waveform. AE parameters such as hit counts, hit rate, RMS, energy, peak amplitude, rise time and counts-to-peak were recorded to capture micro-scale events; such AE descriptors are established in rolling-bearing condition monitoring [9, 11, 16].

2.6. Test Protocol and Data Handling

Each test began with a 5-minute run-in period under clean lubrication, after which the contaminated lubricant formulation was introduced into the system. Vibration, AE, temperature and friction torque were recorded simultaneously during the contaminated phase. The acquired data were segmented into 1-second windows with 50% overlap for feature extraction. Pre-processing steps included detrending, DC offset removal and band pass filtering. Vibration data were filtered between 2–10 kHz, while AE data were filtered between 100–500 kHz to isolate high-energy transient events. High-frequency AE analysis is widely used to detect incipient rolling-contact events [17].

2.7. Wear Measurement and Post-Test Surface Characterization

Upon completion of each test, the bearings were disassembled, and the raceways were examined to quantify wear. A non-contact 3D optical profilometer was used to determine the wear depth, width, and volume of the bearing surfaces. The instrument provided a vertical resolution of 10 nm and a lateral resolution of 1 μm over a scan area of $5 \times 5 \text{ mm}^2$, allowing the wear volume and surface topography to be measured. The worn bearing raceways were subsequently examined using Scanning Electron Microscopy (SEM) coupled with Energy-Dispersive Spectroscopy (EDS). SEM was used to evaluate the surface morphology, including ploughing marks, pits, micro-cracks, embedded particles, and tribofilm features, while EDS was used to identify the elemental composition associated with the observed surface regions. The SEM-EDS observations were used to relate the surface morphology and elemental distribution to the vibration, acoustic emission, and wear responses obtained during the tests.

X-ray Photoelectron Spectroscopy (XPS) was further used to examine the surface chemical states associated with the interactions of WS_2 , GNP, and Al_2O_3 with the bearing raceway. The analysis was used to identify the chemical bonding characteristics of the elements present on the worn surfaces and to provide supporting evidence for tribofilm formation. Raman spectroscopy was used as a complementary structural characterization technique. The Raman analysis was

performed on the post-test worn surfaces to identify characteristic spectral features associated with WS_2 , graphene-based carbon, and Al_2O_3 , together with possible structural changes or stress-related spectral shifts. The SEM-EDS, XPS, and Raman observations were considered together with the vibration, acoustic emission, and wear results to support the interpretation of the tribological mechanisms of the tested nano-additives.

2.8. Statistical, Performance Index and Machine-Learning Analysis

The experimental results were evaluated using one-way Analysis of Variance (ANOVA) to determine whether significant differences existed among the four lubricant conditions for vibration RMS, AE RMS, and wear rate. Where significant differences were observed, Tukey's post-hoc test was used for pairwise comparison, with statistical significance considered at $p < 0.05$. For the multi-sensor assessment, a Performance Index (PI) was calculated using the vibration RMS, AE RMS, envelope peak amplitude, and wear rate. The measured parameters were first normalized and then combined using inverse weighting according to their contribution to surface degradation, so that higher PI values represented more favourable combined diagnostic behaviour.

A Random Forest (RF) classifier was used to distinguish the responses of the tested lubricant conditions based on vibration RMS, AE RMS, envelope peak amplitude, spectral band energy, AE counts, and AE energy. The dataset was divided into 70% training and 30% testing subsets using stratified sampling to preserve the class distribution. Classification performance was evaluated using accuracy, precision, recall, confusion matrix, and feature importance.

3. Results and Discussion

3.1. Vibration Time-Domain Response

The time-domain vibration response of the bearing under different nano-additive formulations provides the first indication of how each lubricant interacts with the contaminated contact. Figure 2 shows representative acceleration waveforms recorded during the steady-state phase of operation for the base oil, WS_2 , GNP and Al_2O_3 formulations under quartz contamination. The base oil exhibited noticeable amplitude fluctuations, categorized by intermittent spikes that correspond to the direct impact of abrasive particles entering the rolling contact. In reality, these prominent transient events have shown the unstable lubrication conditions and successive increased asperity interactions. In the surprise, the WS_2 formulations have demonstrated a significant smoother vibration profile with distinct reduce peak to peak variations. Mostly, this behaviour was consistent with the possible formation of a low-shear-strength WS_2 film, a mechanism reported for WS_2 lubricant additives [7].

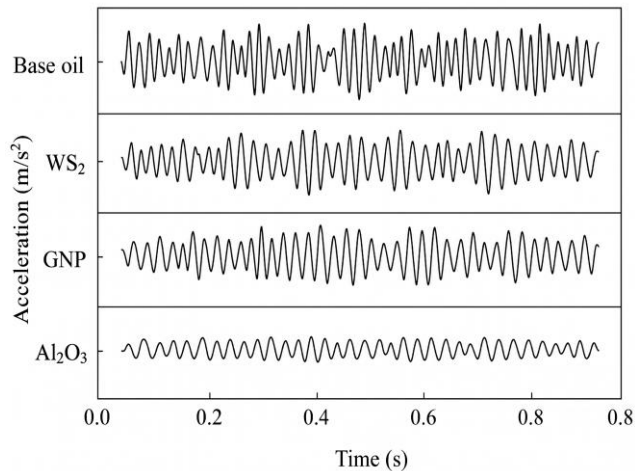


Fig. 2 Time-domain vibration response

Moreover, the GNP particle added formulations have shown similar trends, with inferior amplitude bursts and a proactive uniform waveform envelope, indicating improved damping and stabilization of the rolling interfaces, as the evident of possible carbon-rich protective layers. Whereas the aluminium oxide formulations have behaved in an indifferent way, intact produces larger and more redundant transient vibration spikes as compared with all other formulations. Meanwhile, the presence of hard ceramic particles in combining the quartz contaminants intensifies micro-cutting and indentation events, resulting in repeated high-energy impulses observable as the waveform.

The increase irregularity of the vibration signal in this case corresponds to aggravated abrasive interactions and unstable lubrication films. Generally, the time-domain vibration analysis clearly differentiates synergistic additives (WS₂ and GNP) from antagonistic behaviour (Al₂O₃). The reduction in impulsiveness and smoothing of vibration waveforms for WS₂ and GNP formulations is consistent with protective-film mechanisms reported for layered and graphene-based lubricant additives [18, 19]. In the present contaminated tests, the comparatively stronger impulsiveness of the Al₂O₃ formulation indicates more severe abrasive interaction.

3.2. Acoustic Emission Characteristics

Acoustic Emission (AE) monitoring provides useful information on microscale events occurring at the bearing contact under different lubrication conditions. Previous work has shown that AE parameters can distinguish between dry and lubricated rolling bearings, supporting the use of AE as a sensitive indicator of lubrication-related changes [20]. Figure 3 categorically reveals the representation of AE waveforms acquired for the four lubricant preparations under the indistinguishable working circumstances. Normally, vibration signals are meant to capture macro-scale dynamic responses, whereas the AE signals possibly originate from the high-

frequency stress waves which concurrently generated by severity fracture followed by particle impacts and tribofilm rupture. Also, it was found that the base oil significantly exhibits a large number of transient bursts with prominent high amplitudes, which possibly indicates the frequent abrasive collisions between the quartz particles and matting rolling elements.

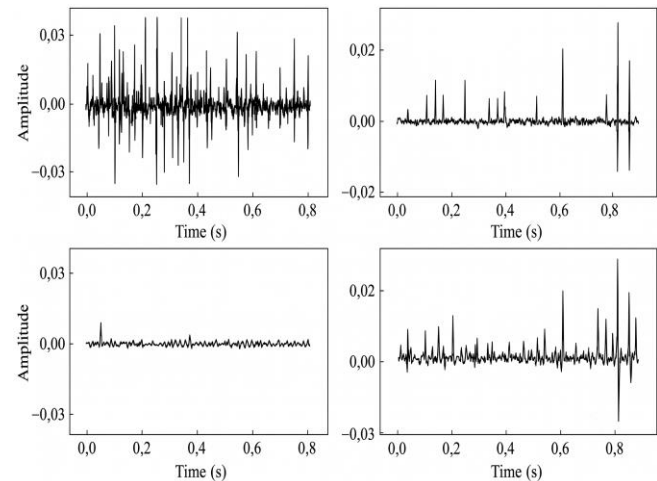


Fig. 3 AE time-domain signals for different nano-additive lubricants under contamination

Actually, this set of high-energy AE conceivably hits, corresponding to unstable boundary lubrication and originates the repeated micro-crack initiation at the contact interface feasibly. Whereas the WS₂ combinations reveals the noteworthy decrease in the value of AE activity, similarly between the amplitude and hit count were seemed to be much lower as compared to the base oil, compassionately which shows the WS₂'s capability to form a lamellar tribo-film, intact it cushions the particulate impacts and simultaneously suppresses high frequency stress wave generation, in addition to that, this trend of smoother waveform profile, concurrently reveals the rarer asperity fracture events, which consistent with the additive lubricant behaviour and hard affinity, towards forming protective films under the notable of mixed lubrication circumstances. Similar to the preceding obtained values of WS₂, GNP also exhibits a similar set of improvements, which shows the substantial weakened AE bursts, which adherently have the direct relation with the base oil. As well, the presence of carbonaceous layers, which are directly derived from the graphene, acts as the transfer films and predominantly absorbs the energy at the contact, thereby preventing the abrupt release of elastic shock waves that inherently generate the sharp AE spikes. In line with the above, the waveform distribution of GNP directly indicates a more stable surface interaction system with shows the reduce in the abrasive severity [6, 24]. Contrarily, the so-called aluminium oxide formulations are set to produce many more AE bursts as compared with the remaining all contaminations. In actual, the combination of aluminium oxide nanoparticles

and quartz particulates has successively initiated the severe micro cutting and indentation events, which adherently produced a high frequency of strong and narrow AE spikes. In addition to that, this kind of behaviour is about to reflect the mechanically aggressive interactions due to consistent amplified abrasive wear. These massive amplitude transients are unswervingly associated with redundant contact disruptions and subsequent tribofilm breakdown, which concurrently proves the antagonistic nature of aluminium oxide under the contaminated circumstances. In the conclusion, AE analysis obtained with the different formulations has successively differentiated the time domain response in a sharper manner.

Similarly, WS2 and GNP formulations have showed noteworthy weakening on high frequency transients, which profoundly process the active and protective tribo-films, which successfully absorb or dissipate the mechanical energy. Contrarily, the aluminium oxide exhibited the irrelevant trend, with sharply intensified AE activity, which also represents surface instability, followed by abrasive interactions. Further, these observations are aligned with the tribo-film and wear mechanisms, which have been established in previous studies and reinforce the sensitivity of AE as a premature diagnostic tool in order to evaluate lubricant additive performances under contamination environments [21].

3.3. Frequency-Domain Vibration Analysis

The Figure 4 illustrates the Fourier spectra analysis of four lubricant formulations under different circumstances. Actually, the frequency domain analysis has been initiated in order to exhibit how nano-additives have a significant influence in spectral characteristics of bearing vibration under the circumstances of contaminated lubrication. The strong broadband energy was noticed across the region of 1-8 kHz with respect to base oil; apart from that, distinct high amplitude peaks were also successively noticed with repeated quartz particulate impacts. These broadband components are primarily associated with third-body particle impacts and intermittent asperity contacts occurring at the rolling interface under unstable lubrication conditions. Furthermore, these sets of spectral signatures have prominently indicated the contact conditions as well as severe micro-indentation events upon the rolling interface. As an advantageous response, the WS2 formulation showed a substantial decrease in high-frequency spectral density, especially above 4 kHz.

Frequency-domain and envelope-based methods are established tools for identifying impact-related bearing signatures [15, 23]. This reduction indicates effective damping of impact-induced vibrations due to the formation of a continuous lamellar tribofilm that limits direct particle-metal interactions. Besides, predominantly suggests an effective suppression of impact-induced heavy vibrations through the formation of a lamellar tribofilm. Meanwhile, the WS2 formulations exhibited a considerable reduction in high-

frequency spectral, in parallel to the same, GNP also showed. To the surprise of the experimental outcome, WS2 formulations have exhibited a considerable negative dip in high-frequency spectral, also GNP reveals a decrease in spectral amplitudes across the high and mid frequency bands. Actually, this incredible process reflects the stabilizing effect of carbonaceous transfer films upon the lubricated contact of the bearing surface. However, the aluminium oxide formulation simultaneously produces pronounced spectral heights and elevated energy broadband levels, which in turn indicates the stronger abrasive interactions and recurrent level of impact events profoundly. The presence of hard ceramic particles intensified particle-induced impacts and micro-cutting events, resulting in persistent high-frequency excitation. Overall, the frequency-domain results support the time-domain observations: WS2 and GNP produced lower contamination-induced excitation, whereas the Al_2O_3 formulation produced stronger high-frequency vibration under the present test conditions.

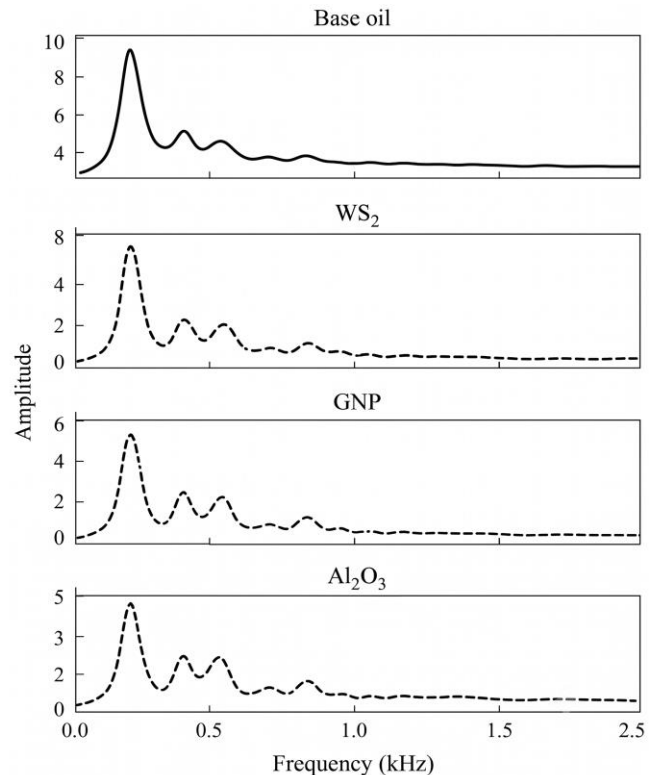


Fig. 4 Power spectral density (PSD) comparison of vibration signals for base oil, WS2, GNP and Al_2O_3 formulations under contaminated lubrication (0-2.5Hz).

3.4. Correlation Between Vibration, Acoustic Emission and Wear Mechanisms

A synergistic assessment on vibration, acoustic emission and post-test wear mechanism behaviour suggestively provides a higher level of insights into the tribological response of each nano-additive under the contaminated lubrication circumstances.

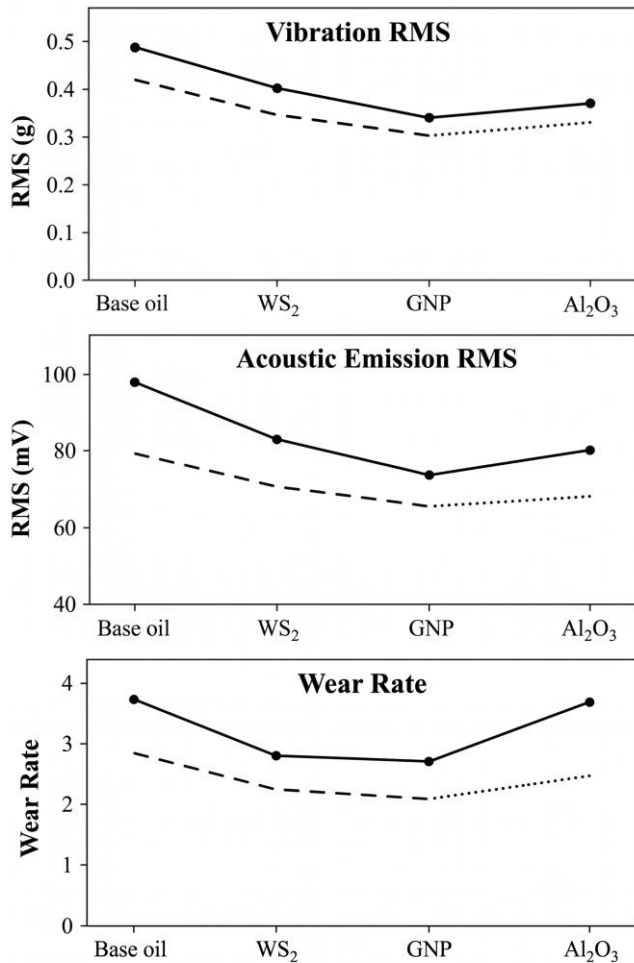


Fig. 5 Vibration RMS, AE RMS and wear rate trends for different nano-additive lubricants.

Figure 5 illustrates a direct and cumulative quantitative relationship between vibration RMS, AE RMS and wear rate consecutively, which enables integrated interpretation of dynamic excitation and eventually material removal mechanisms. Further to evaluate the mechanism behind the experimental processes, base oil exhibited a vibration RMS value of 0.42 g and AE RMS of 82 mV, resulting in the successive wear rate of $3.25 \times 10^{-7} \text{ mm}^3/\text{N}\cdot\text{m}$. One-way ANOVA performed on vibration RMS, AE RMS and wear rate revealed statistically significant differences among lubricant formulations ($p < 0.01$), confirming that the observed trends are not due to random variability. Meanwhile, these values indicate a comparatively unstable lubrication response dominated by repeated particle-induced impacts and abrasive sliding. Further to this, the correlation between elevated RMS values and higher level of wear confirms that increases dynamic excitation simultaneously accelerates surface degradation. Similarly, WS₂ lubricated bearing surfaces have showed a vibration RMS reduction of 0.28 g, that was obviously 33% decrease with preceding parameter and the another notable AE RMS value that have been found

to be as 49 mV, that too was also 40% decrease in value, and finally wear rate was found to be as $1.12 \times 10^{-7} \text{ mm}^3/\text{N}\cdot\text{m}$, which was also 65% reduction against the values found in the base oil. Moreover, this strong found values upon the combinations clearly demonstrates that suppression of both high frequency and low frequency vibration AE directly translates into a decrease in material loss. In addition, GNP also significantly showed improved performance, with vibration RMS of 0.31 g and AE RMS of 56 mV, leading to a wear rate of $1.48 \times 10^{-7} \text{ mm}^3/\text{N}\cdot\text{m}$, corresponding to a 55% reduction. In contrast, Al₂O₃ have exhibited vibration RMS of 0.47 g and AE RMS of 91 mV, resulting in a wear rate of $3.05 \times 10^{-7} \text{ mm}^3/\text{N}\cdot\text{m}$, which closely aligns with the value of the match of base oil. The near-linear proportionality between dynamic RMS values and wear rate confirms the suitability of vibration and AE metrics as predictive indicators of tribological severity under contaminated conditions. The near-linear proportionality among RMS values and wear rate across all formulations supports the use of the measured dynamic metrics as indicators of tribological severity in the present dataset.

The friction torque and lubricant temperature measurements were also considered as supporting indicators of the tribological response under contaminated lubrication. The friction response was evaluated together with the vibration and acoustic emission signals to identify changes associated with particle-induced contact disturbances and protective tribofilm formation. Similarly, the monitored lubricant temperature provided an indication of frictional heating during the tests. The combined observations were consistent with the vibration, acoustic emission, and wear responses, with the film-forming WS₂ and GNP formulations showing more stable tribological behaviour than the Al₂O₃ condition.

3.5. Mechanistic Interpretation of Nano-Additive Performance

It was observed that the unified diagnostic trends obtained from vibration RMS, AE RMS, PSD behaviour and wear measurements consecutively enable a unified mechanistic interpretation of how each nano-additive particulate behaves under the contaminated lubricated circumstances. Furthermore, the PSD spectrum also reveals elevated energy broadband, which adherently indicates reputed micro-impact events and asperity disruptions.

As well, through the analysis, it was observed that, WS₂ formulations clearly gives the best performance, in that sequel of obtained values, the vibration RMS reduced to 0.28 g (reduction of 33% from base oil), AE RMS conversely shows the reduce in the value of 49 mV (40% decrease in value), and wear rate successively lowered to $1.12 \times 10^{-7} \text{ mm}^3/\text{N}\cdot\text{m}$ (65% reduction). The dominance of low-energy vibration and reduced AE bursts indicates effective tribofilm coverage that absorbs impact energy and prevents tribofilm rupture. From

the discussions, it was clearly seen that these reductions obviously suggest the formation of a solid and robust lamellar tribofilm that proactively absorbs shock loads and consecutively prevents direct metal-to-metal contact. Also, the diminished high-frequency PSD peaks and fewer AE bursts absolutely support the presence of a shear-resistant film that possibly buffers the particle intrusion. As towards to achieve the systematic approach, WS₂ platelets oriented themselves absolutely parallel to the sliding direction, which proactively generates a low-shear protective layer that moderately stabilizes both friction and vibration responses. In addition to the above, GNP also in their part, exhibits substantial improvements in the relevance to the base oil, the found vibration value of RMS was 0.31 g, which have been seen as 26% dip with based oil, as well AE RMS have shown the value of 56 mV, also this was nearly 32% of reduction with base oil, and eventually wear rate was found as 1.48×10^{-7} mm³/N·m (55% decrease).

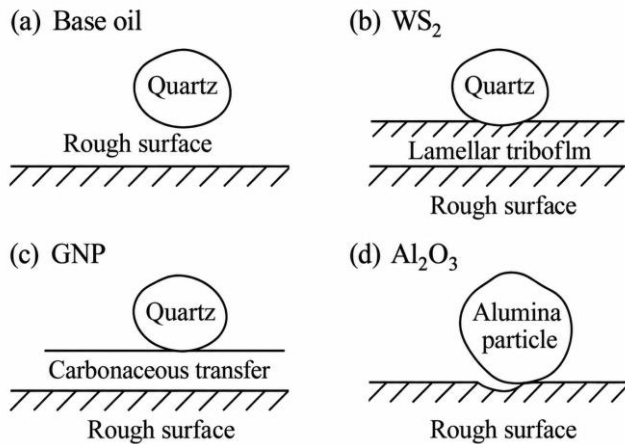


Fig. 6 Tribofilm versus abrasion.

The obtained values indicate moderate suppression of PSD energy and AE transients, consistent with carbonaceous transfer-film mechanisms reported for graphene-based lubricant additives [6, 24]. These layered grapheme sheets actively distribute load with more effective way and act as a mechanical buffer during particle impacts. Though GNP is not able to achieve the same level of damping as such as WS₂, but its mechanistic behaviour clearly indicates a synergistic interaction between nano-layers and the rolling contact, also it positively leads to smoother dynamic responses and a decrease in abrasive wear. On the other hand, the Al₂O₃ formulations have shown tainted performance, with vibration RMS increasing to 0.47 g, AE RMS rising to 91 mV, and wear rate reaching 3.05×10^{-7} mm³/N·m, closely matching the base oil. Feature-level interpretation indicates that moderate AE activity corresponds to partial tribofilm coverage and load-sharing by graphene sheets, resulting in stable but less compact protection compared to WS₂. Contrarily, the increased PSD energy and the subsequent dense clusters of AE

spikes practically confirm intensified abrasive interactions caused by the presence of hard and angular aluminium oxide particles. Actually, these particles are not able to form protective films; instead, they act as micro-cutting tools that actively amplify impact severity. Essentially, this mechanistic pathway absolutely dominates repeated indentation, tribo-film removal and consecutive accelerated material removal. Largely, the mechanistic interpretations have strongly confirmed good agreement across all diagnostic channels. As a result, additives are capable of forming stable tribofilms (WS₂, GNP), which steadily exhibit reduced dynamic excitation and wear, whereas additives lacking this ability (Al₂O₃) and amplifies both the parameters. The dominance of high-energy AE transients reflects repeated micro-cutting and tribofilm removal events rather than protective film formation. Moreover, the joint substantiation reinforces the value of multi-sensor condition monitoring as a predictive tool for lubricant additive performance assessment under harsh conditions [3].

3.6. Envelope Spectrum Analysis

Commonly, envelope analysis was executed in order to evaluate the modulation effects induced by contaminant particles that enter the rolling contact. Furthermore, this technique is said to be highly sensitive to impact-type events and is generally adopted to identify early-stage bearing interactions that could not be clearly seen in the raw time-domain signals.

Figure 7 exhibits the Hilbert-transformation envelope spectra of the four different sets of lubricated conditions, and also shows the characteristic fault frequency regions. As the initial exploitation, base oil showed prominent spectral peaks near the Ball-Pass Frequency (BPFO) of the outer race of the bearings, as well as showing the harmonics, which indicates frequent particulate-induced impacts as the rolling elements successively pass over the embedded quartz particulates. These BPFO-related modulations arise from repetitive third-body impacts and intermittent asperity contacts occurring at the rolling interface under unstable lubrication conditions. In addition, this set of elevated amplitudes across the races prominently shows the harmonics and successively confirms that abrasive interactions were routinely initiated to excite the structural (resonance) elements of the bearing system. As the surprise note, the WS₂ formulations exhibited remarkable amplitude in connection to the BPFO band, where peak magnitudes were about to decrease by nearly 45% against the based oil.

This attenuation reflects the ability of the lamellar WS₂ tribofilm to dissipate contact stresses and suppress periodic impact modulation associated with abrasive particle entrainment. Moreover, this attenuation possibly reflected the ability of the lamellar WS₂ tribofilm in order to disperse contact stresses and suppress modulation attire, which is associated with repetitive impacts. Secondary harmonic peaks

also weakened, indicating reduced periodic excitation during rolling. The interpretation is consistent with the reported dispersibility and tribological performance of WS₂ nanosheets in lubricating oil [25].

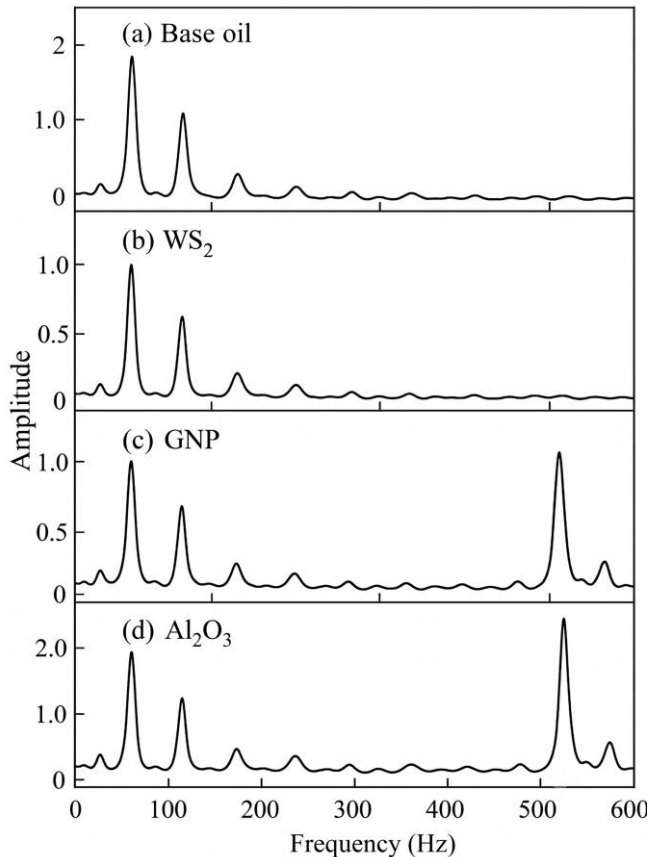


Fig. 7 Envelope spectra comparing impact-related frequency components for different nano-additive lubricants under contamination.

Additionally, GNP reveals similar improvements, exactly reducing the BPFO amplitudes by approximately 32%. The flatter spectral floor suggests reduced variability in impact severity, attributed to the presence of graphene-derived transfer films that distribute contact loads and minimize force fluctuations at the asperity level. Also, the found broad spectral floor was completely flattened as compared to the base oil, which possibly indicates the decrease in variability in impact severity.

The main reason behind this evident, possibly, could be the presence of graphene-based transfer films, which help to distribute load and minimize the asperity level of force fluctuations, which directly translates to reduced demodulated spectral content. As possibly expected, the Al₂O₃ formulations have initiated the strongest envelope peak, which consecutively exceeds the base oil amplitude by almost by 18%. The hard, angular particles intensified repetitive impact events, generating strong modulation sidebands and harmonic patterns consistent with severe abrasive interaction.

Furthermore, as the evident of the same, the hard and angular particulates intensifies high energy impacts, vice versa generates strong modulation sidebands and clear harmonic patterns. Also, this foreseen behaviour aligns well with the elevated RMS values, as well as severe wear observed in earlier studies. As a whole, the envelope analysis positively reinforces the performance ranking observed across all the diagnostic domains. These observations indicate that the film-forming additives used here suppressed characteristic impact frequencies, consistent with reported WS₂ lubricant-additive behaviour [22].

3.7. Statistical Evaluation of Diagnostic Parameters

The Figure 8 entirely labels the statistical analysis of vibration RMS, AE RMS, and wear rate against each lubricated condition, as well as provides insight into the repeatability and stability of all bearing surfaces. It was found that WS₂ exhibited a lower level of standard deviation throughout all parameters. As is evident, the found variability was nearly 2.5 times less than that of the base oil, and it solely acknowledges that low dispersion indicated consistent tribofilm formation across the surfaces, as well evidences the stable dynamic behaviour throughout tests. The hard, angular particles intensified repetitive impact events, generating strong modulation sidebands and harmonic patterns consistent with severe abrasive interaction. Similarly, GNP have showed moderate variability; the found standard deviations were nearly 1.8 times lesser than the base oil, which reflects noticeable and consistent performance, but proves the possibility of occasional fluctuations in tribofilm coverage. In the contrary, Al₂O₃, in combination with base oil, exhibits the highest variability, which strongly implicates unpredictable abrasive interactions and unstable lubrication regimes. Furthermore, reduced statistical scatter is particularly meant for condition monitoring applications, because it positively enhances diagnostic reliability and confidence in predictive maintenance decisions. Also, the statistical trend further evaluates the superiority of tribofilm-forming additives in contaminated environments.

The WS₂ formulation not only reveals the lowest mean values, but also the least spread, by showing the standard deviation of ± 0.02 g, ± 4 mV, and $\pm 0.18 \times 10^{-7}$ mm³/N·m, correspondingly. Moreover, the findings predominantly prove the repeatability of WS₂ tribofilm formation mechanism and its reliable ability to attenuate dynamic excitation. Likewise, GNP also showed stable behaviour, with modest deviations, reflecting the uniform distribution of graphene sheets and their reproducible transfer film behaviour across frequent trials. As such, contrary values obtained from the previous studies upon the Al₂O₃, the Al₂O₃ formulations prominently show significant dispersion, as like as the base oil, by showing the RMS variation of ± 0.06 g, AE variation of ± 8 mV, and wear-rate deviation of $\pm 0.39 \times 10^{-7}$ mm³/N·m. In addition to the above, the abrasive nature of Al₂O₃ particulates and their impulsive interactions with quartz contaminants result in

inconsistent high-energy impact events, thus producing large statistical scatters. Moreover, this behaviour is also replicated in the envelope spectra; in such circumstances, amplitude variations seem to appear more irregular as compared to WS₂ and GNP.

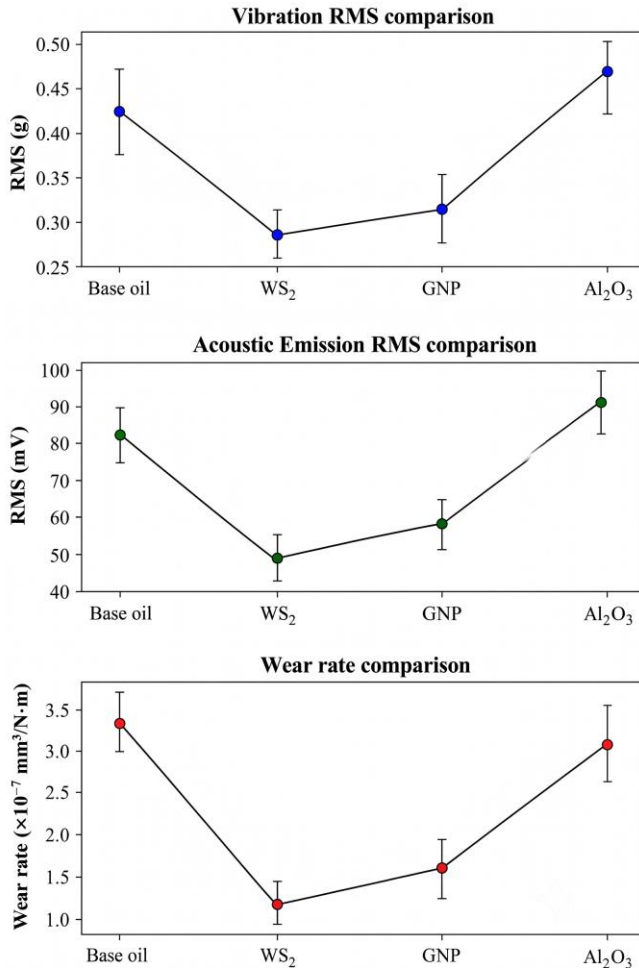


Fig. 8 Statistical comparison of vibration RMS, acoustic emission RMS, and wear rate for bearings lubricated with base oil, WS₂, GNP, and Al₂O₃ under contaminated conditions.

Generally, the statistical analysis deliberately confirms the stability ranking as similar to previous identified from dynamic and tribological trends; as shown, WS₂ have most stable, likely follows in a declining way that, GNP follows with Base oil and finally ends up with Al₂O₃ (least stable). Post-hoc Tukey analysis indicated that both WS₂ and GNP differed significantly from Al₂O₃ and base oil conditions ($p < 0.05$). The use of nano-additives thus the way induces the uncertainty and dynamic instability. Besides, this reinforces the robustness of WS₂ and GNP as found as the effective modifiers in contaminated lubricated circumstances. The inclusion of statistical significance testing strengthens the robustness of the proposed diagnostic framework and supports its applicability in contaminated lubrication environments.

3.8. Multi-Sensor Correlation Matrix and Performance Index Evaluation

In order to precisely establish a combined diagnostic interpretation, a multi-sensor correlation analysis has been performed by using the vibration RMS, AE RMS, envelope peak amplitude, and finally wear rate as believed to be the primary indicators.

Vibration RMS	1.00	0.86	
AE RMS	0.78	0.91	1.00
Envelope Peak	0.91	0.88	0.88
Wear Rate	0.79	0.79	1.00
	Vibration RMS	AE RMS	Envelope Peak

Fig. 9 Correlation matrix of diagnostic parameter

Figure 9 depicts the correlation matrix, thus the way it highlights the strong interactions among the measured parameters and ropes the mechanistic insights as such discussed in previous sections. It was seen that a strong positive relationship ($r=0.86$) have been witnessed between AE RMS and vibration RMS, which possibly indicates that the combination of sensors has responded towards the impact-driven interactions that have been generated during the contaminated rolling. Likewise, the correlation between envelope peak amplitude and AE RMS was also a bit higher ($r=0.91$), which obviously reflects the fact that demodulated signals are predominantly highly sensitive to frequency transient events captured by AE. Similarly, wear rate has also demonstrated a strong and positive correlation with vibration RMS ($r=0.81$) and AE RMS ($r=0.88$). The data obtained indicate that higher dynamic excitation is associated with increased material removal in the present dataset. Furthermore, the aligned data support the hypothesis that the different sets of lubricant formulations are capacity of dampening high frequency impulses and are also more effective in suppressing abrasive wear. The WS₂ and GNP have shown consistently lower values upon all the parameters and are heavily clustered in the low severity region on the correlation matrix, which directly indicates stable tribological behaviour and real tribofilm formation. However, Al₂O₃ and base oil have been witnessed near the high-severity region, also witnessing poor damping capability and elevated wear. Besides, the Performance Index (PI) was also further

calculated by normalizing and inversely weighting each parameter relative to its contribution to surface degradation. The analysis showed that WS₂ had a PI value of 0.91, followed by GNP at 0.83, base oil at 0.42, and Al₂O₃ at 0.38. These values are consistent with the mechanistic observations discussed earlier and provide an overall comparison of the multi-sensor responses obtained for the four lubricant formulations.

3.9. Random Forest Classification and Physical Interpretation of Features

To assess how well the vibration and acoustic emission features could differentiate the tested formulations, a Random Forest (RF) classifier was used to distinguish the synergistic nano-additives (WS₂ and GNP) from the antagonistic Al₂O₃ additive under contaminated lubrication conditions.

Table 1. Relationship between diagnostic signal features, wear severity, and underlying tribological mechanisms under contaminated lubrication

Diagnostic Parameter	Observed Trend	Associated Wear Behavior	Underlying Tribological Mechanism
Vibration RMS	High for base oil and Al ₂ O ₃ ; low for WS ₂ and GNP	Severe abrasive wear for base oil and Al ₂ O ₃ ; reduced wear for WS ₂ and GNP	Elevated RMS indicates unstable rolling contact and frequent third-body particle impacts; reduced RMS reflects stabilized contact due to protective tribofilm formation
AE RMS	High for Al ₂ O ₃ and base oil; significantly reduced for WS ₂ and GNP	High material removal and surface damage for Al ₂ O ₃ ; mild wear for WS ₂ and GNP	High AE RMS corresponds to repeated micro-fracture, asperity breakage, and tribofilm rupture; reduced AE RMS indicates energy dissipation by lamellar or carbonaceous films
AE counts / hit rate	Dense, frequent hits for Al ₂ O ₃ ; sparse hits for WS ₂ and GNP	Aggressive micro-cutting and indentation for Al ₂ O ₃ ; suppressed abrasive events for WS ₂ and GNP	High hit rate reflects continuous particle-induced impacts; low hit rate indicates effective shielding of contact by tribofilms
Envelope peak amplitude (BPFO region)	Strong peaks for base oil and Al ₂ O ₃ ; attenuated peaks for WS ₂ and GNP	Pronounced impact-driven wear for Al ₂ O ₃ ; stable rolling contact for WS ₂ and GNP	High envelope amplitudes arise from repetitive third-body impacts; reduced amplitudes reflect damping of impact forces by tribofilm coverage
High-frequency spectral energy (PSD)	Elevated for Al ₂ O ₃ ; suppressed for WS ₂ and GNP	Enhanced abrasive interaction for Al ₂ O ₃ ; reduced surface excitation for WS ₂ and GNP	Broad high-frequency energy corresponds to particle-induced excitation; suppression indicates smoother contact and load sharing.
Wear rate	Maximum for base oil and Al ₂ O ₃ ; minimum for WS ₂	Severe surface degradation for Al ₂ O ₃ ; minimal wear for WS ₂ and GNP	Direct consequence of tribofilm stability: protective films reduce metal-to-metal contact, while abrasive particles accelerate material removal
Random Forest feature importance	AE RMS and envelope peak dominant for Al ₂ O ₃ ; reduced importance for WS ₂ and GNP	Clear classification of antagonistic vs synergistic additives	Dominant features reflect impact severity and tribofilm rupture, linking machine-learning output to physical wear mechanisms

Table 1 shows the relationship between the diagnostic signal features, wear severity, and the underlying tribological mechanisms under contaminated lubrication. A Random Forest (RF) classifier was used because it can handle noisy data, nonlinear feature interactions, and relatively small experimental datasets. The experimental runs were separated into training and testing groups before signal-window segmentation. Two complete runs from each lubricant condition were considered for model training, while the remaining complete run was reserved for independent testing. All overlapping windows generated from a given test run were retained within the same data partition to avoid information

leakage between the training and testing datasets. The input features included vibration RMS, AE RMS, envelope peak amplitude, spectral band energy, AE counts, and AE energy. Model performance was assessed using classification accuracy, the confusion matrix, and feature importance. The RF classifier showed effective discrimination among the tested lubricant conditions, with the confusion matrix indicating limited misclassification between the film-forming WS₂ and GNP conditions. The feature-importance analysis further identified AE RMS, envelope peak amplitude, and vibration RMS as important diagnostic features.

The feature importance analysis also helped relate the classification results to the observed tribological behaviour. AE RMS, envelope peak amplitude, and vibration RMS were identified as the most influential features. Higher AE RMS and envelope amplitudes were associated with repeated third-body impacts and tribofilm disruption, while lower values were associated with more stable tribofilm formation and load sharing. Vibration RMS mainly reflected the stability of the overall rolling contact, whereas the AE features were more sensitive to microscale fracture and impact events. The WS₂ and GNP samples generally showed lower impact-related feature contributions, consistent with effective tribofilm coverage and energy dissipation. In comparison, Al₂O₃ showed stronger contributions from high-energy AE bursts and envelope peaks, which corresponded to abrasive micro-cutting and repeated surface disruption. Therefore, the RF results complement the vibration, AE, and surface observations by providing a direct link between the extracted signal features and the observed wear and tribofilm behaviour. The integration of RF classification with physical interpretation strengthens the reliability of the proposed diagnostic framework for industrial bearing condition monitoring [13].

3.10. Post-Test Surface Morphology and Tribofilm Formation (SEM–EDS)

The post-test surface morphology analysis was executed to authenticate the tribological mechanisms inferred from vibration, acoustic emission, and wear measurements. Also, it seemed that, representative SEM micrographs of the bearing raceways lubricated with different nano-additive formulations are shown in Figure 10.

The base oil lubricated surfaces have demonstrated severe abrasive damage categorized by deep ploughing grooves, micro-pits, and localized surface fragmentation. Moreover, these features are significantly indicative of repeated quartz particle indentation and micro-cutting under unstable boundary lubrication conditions. Likewise, the extensive surface damage seen for the base oil correlates well with the high vibration RMS, elevated AE activity, and increased wear rate reported in repeated analysis. In contrast, the WS₂-lubricated surfaces showed a noticeably smoother morphology with shallow grooves and extensive coverage of a compact tribofilm, consistent with the low-shear film-forming behaviour reported for WS₂ lubricant additives [7, 22]. Also, it was found that the absence of deep ploughing marks indicates that the lamellar WS₂ platelets commendably shielded the metal surface from direct particle contact. Along with that, energy-dispersive spectroscopy additionally confirmed the presence of tungsten and sulphur-rich regions homogeneously dispersed along the wear track, supporting the formation of a stable tribofilm. Moreover, this surface defence mechanism elucidates the noteworthy reductions in vibration amplitude, AE burst intensity, and wear rate as observed earlier.

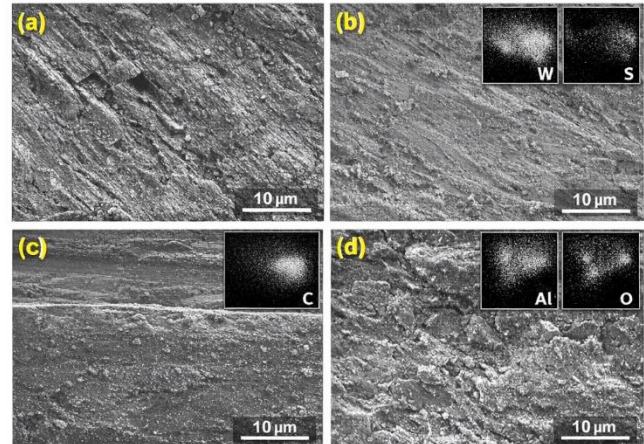


Fig. 10 SEM and EDS analysis of surfaces after tests (a) Base OIL, (b) WS₂, (c) GNP, (d) Al₂O₃.

Similarly, to the same, the GNP lubricated surface demonstrated moderate wear with smoother tracks compared to the base oil, though less uniform than WS₂. In addition to the same, SEM images revealed partial coverage by carbonaceous transfer films scattered with fine abrasion marks. EDS analysis also showed carbon-rich regions on the surface, indicating that the deposited carbonaceous layer may have contributed to load sharing and energy dissipation during particle impacts. In contrast, the Al₂O₃-lubricated surface exhibited severe abrasive damage, comparable to or greater than that observed for the base oil. Deep grooves, micro-cracks, and embedded debris were clearly observed, indicating that the hard-ceramic particles promoted micro-cutting rather than surface protection. These surface features are consistent with the trends observed in the vibration and AE measurements and support the relationship between protective tribofilm formation and reduced dynamic excitation under contaminated lubrication [26].

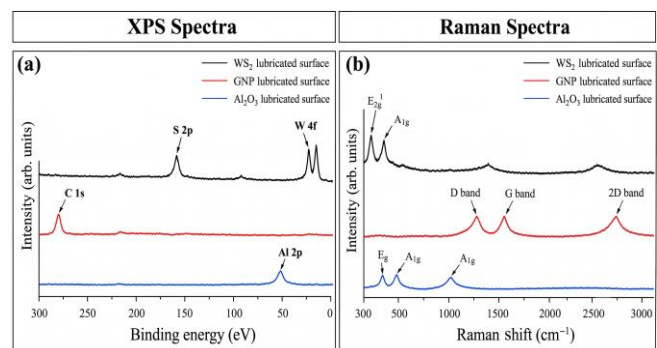


Fig. 11 Schematic representation of (a) XPS spectra and (b) Raman spectra illustrating the characteristic chemical signatures associated with WS₂-, GNP-, and Al₂O₃-lubricated surfaces under contaminated conditions.

3.11. Chemical and Structural Characterization of Tribofilms (XPS and Raman)

X-ray Photoelectron Spectroscopy (XPS) and Raman spectroscopy were used to further support the interpretation of

tribofilm formation based on the vibration, acoustic emission, and wear results. Figure 11 schematically presents the representative spectral features associated with the WS₂, GNP, and Al₂O₃ lubricated surfaces under contaminated rolling conditions.

These techniques were used to provide additional information on the chemical bonding and structural characteristics of the tribofilms identified from the vibration, acoustic emission, and wear results. For the WS₂-lubricated condition, the XPS results indicated tungsten–sulfur bonding states, supporting the formation of a lamellar WS₂ tribofilm on the bearing raceway. Such low-shear WS₂ films have been reported to reduce friction and direct asperity interactions [7, 22]. The Raman results further supported this interpretation through the characteristic vibrational features of WS₂, indicating that the film retained its structure during the test. This behaviour is consistent with the reduced high-frequency AE bursts, lower envelope amplitudes, and lower vibration RMS values observed in the earlier analyses.

For the GNP-lubricated bearings, the XPS results showed dominant carbon-related bonding states, suggesting the formation of graphene-derived transfer layers on the steel surface. The Raman spectra also showed the characteristic D and G bands of graphene, supporting the presence of carbonaceous films that can assist in load distribution and energy dissipation. Although these films may not be as compact as the WS₂ tribofilm, they still provide interfacial protection and contribute to load sharing, which is consistent with previous studies on WS₂/graphene nanocomposite lubricants [8].

This interpretation agrees with the moderate and consistent reductions in vibration, AE activity, and wear observed for the GNP formulation. In contrast, the Al₂O₃-lubricated condition mainly showed chemical features associated with aluminium–oxygen bonding, with no clear indication of a lubricious tribochemical film. The Raman results likewise showed no distinct signatures of a protective phase. The surface behaviour was therefore dominated by abrasive interactions, including repeated micro-cutting and indentation, which corresponded to higher vibration excitation, increased AE activity, and wear comparable to that of the base oil.

Overall, the XPS and Raman results provide additional chemical and structural support for the multi-sensor observations. The film-forming additives, particularly WS₂ and GNP, were associated with lower dynamic excitation and wear under contaminated lubrication, whereas Al₂O₃ was associated with stronger abrasive interactions. These results further support the use of vibration and acoustic emission measurements for relating changes in bearing signals to the underlying tribological behaviour of nano-additive lubricants.

4. Conclusion

The study examined the performance of different nano-additives in rolling bearings under contaminated lubrication using vibration, Acoustic Emission (AE), envelope spectrum, and wear measurements. These measurements were combined to relate the observed dynamic responses to the resulting surface damage. The base oil showed relatively high vibration RMS (0.42 g), AE RMS (82 mV), and wear rate (3.25×10^{-7} mm³/N·m), indicating unstable lubrication and severe abrasive interaction caused by quartz particle contamination. Among the tested additives, WS₂ showed the most favourable performance. Compared with the base oil, it reduced vibration RMS by about 33%, AE RMS by 40%, and wear rate by 65%.

This behaviour was mainly associated with the formation of a stable lamellar tribofilm, which helped absorb impact energy, reduce local stress concentrations, and limit high-frequency excitation. GNP also reduced vibration, AE activity, and wear, although its effect was slightly lower than that of WS₂. The carbon-based transfer film formed by GNP helped improve load distribution and maintain a more stable rolling contact. In contrast, Al₂O₃ showed an opposing trend, with higher vibration amplitudes, increased AE activity, and a wear rate comparable to that of the base oil.

The hard-ceramic particles promoted micro-cutting and repeated impacts, which limited the development of protective tribofilms and increased surface damage. The correlation analysis further showed strong positive relationships between vibration RMS, AE RMS, envelope peak amplitude, and wear rate.

These results support the use of combined vibration and AE measurements for assessing the severity of tribological damage. Overall, the results indicate that nano-additives capable of forming protective tribofilms can improve bearing behaviour under contaminated lubrication, whereas abrasive additives can increase wear and dynamic excitation. The multi-sensor diagnostic approach provides a non-intrusive way to assess lubricant performance and relate changes in bearing signals to wear behaviour under practical operating conditions.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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