

# Performance Evaluation of Palm Oil-Based Grease for Wear and Vibration Control in Spur Gears

Adzlan Abu Hasan<sup>1</sup>, Nadiah Aqilahwati Abdullah<sup>2</sup>, Nurul Farhana Mohd Yusof<sup>3\*</sup>

<sup>1</sup> Faculty of Electronic Engineering & Technology,  
Universiti Malaysia Perlis, Pauh Putra Campus, 02600 Arau, Perlis, MALAYSIA

<sup>2</sup> JLL Malaysia Sdn. Bhd,  
Penang Science Park North, 14100 Simpang Ampat, Pulau Pinang, MALAYSIA

<sup>3</sup> School of Mechanical Engineering,  
Universiti Sains Malaysia, 14300 Nibong Tebal, Pulau Pinang, MALAYSIA

\*Corresponding Author: mefarhana@usm.my

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## Abstract

The reliability and efficiency of gear systems are critically dependent on effective lubrication, which minimizes friction and wear between gear teeth. While conventional mineral-based greases are widely used, growing environmental concerns and the demand for renewable alternatives have prompted interest in sustainable lubricants. The formulation of palm oil-based grease and its application in gear systems remain underexplored, particularly regarding tribological performance under dynamic operating conditions. This study addresses this gap by fabricating a custom gear test rig to investigate the surface wear and vibration characteristics of spur gears lubricated with palm olein-based grease enhanced with molybdenum disulfide (MoS<sub>2</sub>) nanoparticles. The experiment was conducted with an applied torque of 0.31 Nm, operating at 300 rpm for 240,000 cycles. Lubrication performance was assessed through surface wear analysis using Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS), while vibration data were collected after 240,000 gear cycles using a data acquisition system. The formulated grease PG was benchmarked against a commercial mineral-based grease. Results indicate that the MoS<sub>2</sub> enhanced palm oil grease exhibits superior tribological behavior, with very small mass loss of  $6.28 \times 10^{-2}$  %, indicating low surface wear. The grease exhibited moderate vibration levels at  $0.8 \text{ m/s}^2$ , performing better than mineral grease MG1 and slightly less effectively than MG2 in suppressing gear vibration. EDS analysis confirmed the presence of MoS<sub>2</sub> elements on the worn gear surfaces, indicating effective film formation and adherence. These findings highlight the potential of palm oil-based grease as a sustainable alternative for gear lubrication, offering superior wear resistance and lower vibration levels for better operational efficiency.

## 1. Introduction

Gears are essential mechanical components used in various machinery to transmit power and motion. In a geared system, lubricating oil plays a critical role in reducing friction and wear by forming a protective film between gear teeth. This film helps prevent wear propagation on gear surfaces, ensuring smooth operation and longevity. For

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optimal lubrication, it is crucial to select a lubricant with suitable properties and continuously monitor key operational parameters, such as lubricant film thickness, specific film thickness, and lubricant degradation [1]-[3]. Gear failures such as wear, scuffing, micro-pitting, spalling, and scoring are directly influenced by lubricant properties, including film thickness, viscosity, and temperature. Elevated temperatures reduce viscosity, weakening the protective lubricant film. When this film deteriorates, gear teeth become more susceptible to failure, leading to increased noise and vibration levels [4]-[6]. Early detection of gear failure is essential to minimize costs and catastrophic failure due to inadequate lubrication. Timely identification of potential gear damage helps prevent unplanned breakdowns, ensuring continuous operation and reducing downtime in production lines.

Lubricants play a crucial role in industrial applications, primarily by reducing friction and wear in mechanical contacts [7]. The key objectives of gear lubrication include minimizing friction, enhancing efficiency, reducing wear and contact stress on gear tooth surfaces, and extending durability and lifespan [8]. Proper lubrication is essential for the reliable operation of machines, gears, and other power transmission components. Inadequate or improper lubrication can accelerate gear failure, leading to issues such as pitting, scoring, and excessive wear. Lubrication is essential between meshing gear teeth to reduce excessive heat, minimize wear, and prevent surface failures [9]. Although mineral oil is widely used as a lubricant across various industries, its limited biodegradability may not meet current environmental standards [10]. Vegetable oils are considered as an alternative to mineral oils for lubricant base oils due to certain inherent technical qualities and their biodegradability [11]. The best option for creating environmentally friendly lubricants is synthetic and vegetable oil-based esters [12]. Vegetable oils are well known with their excellent lubricity due to its ester functionalities. With the nonpolar ends of the fatty acids facing away from the metal surface, the polar heads of the fatty acid chains chemically attach to metal surfaces to allow the formation of monolayer films [13].

Furthermore, palm oil-based grease is well-suited for sensitive environments due to its lower toxicity, renewability, and potential to reduce pollution. With its lower coefficient of friction and strong lubricant film stability, it helps minimize wear on contacting surfaces and enhances the efficiency of mechanical systems [14]. Grease lubrication is commonly used in bearings and gears, particularly in open or exposed systems or where lubrication access is challenging. Grease remains in place longer and requires less frequent reapplication than liquid lubricants. It is primarily composed of base oil and a thickener, with additives incorporated to enhance performance. Grease lubrication also aids in removing and washing away wear debris generated during contact, preventing accumulation on surfaces [15]. Lubricant additives, often in the form of micro- or nanoparticles, improve the performance of base oils [16]. Lubricants with similar viscosities but different additives can exhibit slight variations in gear surface fatigue life and wear rate [17].

Molybdenum disulfide ( $\text{MoS}_2$ ) is a widely used solid lubricant known for its tribological benefits in reducing friction and wear [18]. Composed of sulphur and molybdenum atoms,  $\text{MoS}_2$  functions as a solid lubricant due to its layered structure and the weak interlayer forces. The addition of  $\text{MoS}_2$  particles or flakes, along with other additives, has been shown to effectively reduce interfacial friction [19],[20]. Integrating  $\text{MoS}_2$  nanoparticles into lubricants enhances tribological performance in concentrated contacts across various applications [21],[22].  $\text{MoS}_2$  in lubricating grease significantly improves tribo-film formation, maintaining lubricity even under extreme lubricant starvation. It enhances key properties such as anti-friction performance, load-carrying capacity, wear and corrosion resistance, and temperature stability [23],[24]. Additionally, nanosized  $\text{MoS}_2$  offers lower friction compared to its micro-sized counterpart [25].  $\text{MoS}_2$  nanoparticles exhibited lower friction coefficients and higher wear resistance compared to conventional  $\text{MoS}_2$  particles [18]. This can be attributed to the microstructure of the protective layer formed by the nanoparticles, which acts as an intermediate lubricant between the contacting surfaces. The inclusion of nanoparticles in the lubricant improved surface wear resistance by mending and surface polishing mechanism [24]. Nanoparticles exhibit a mending effect by adhering to the interacting surfaces and compensating for the mass loss [25]. However, the poorly dispersed nanoparticles may reduce surface wear protection [26]. Recent work observed that the use of  $\text{MoS}_2$  in the lithium-thickened palm oil grease has improved the anti-friction [27].

Vibration analysis is a widely recommended method for monitoring machine health and was extensively used in this experiment [28],[29]. Wear not only leads to direct material loss, causing functional failure, but also alters vibration and noise behavior. As a result, vibration analysis is often conducted alongside lubricant film analysis to provide a comprehensive assessment of gear and bearing performance [30]. In experiments characterizing the vibration behavior of roller bearings and lubricant film thickness, a relationship was established between RMS vibration values and lubricant film thickness [31],[32]. Additionally, an increase in vibration levels was observed with surface degradation [33]. Vibration analysis using mesh frequency ( $f_m$ ) revealed that under crack conditions, measured acceleration responses showed a dominance of mesh frequencies at  $4f_m$ ,  $6f_m$ , and their side frequency components. These side frequencies, which correspond to the rotational frequency of the driving gear, became more prominent as crack severity increased [34].

The contact between gear teeth typically involves a combination of rolling and sliding motion along a line contact, which subjects the gear surfaces to complex tribological stresses. Accurate simulation of these contact

conditions is essential for understanding wear mechanisms and improving gear performance. Traditionally, twin-disc test rigs [35],[36] and rolling contact tribometers [37] have been employed to replicate gear contact behavior under controlled laboratory conditions. However, these methods often simplify the dynamic interactions present in actual gear systems, such as vibration, misalignment, and load fluctuations. Moreover, while conventional mineral-based lubricants have been extensively studied, the tribological performance of environmentally friendly lubricants, particularly palm-based greases, remains underexplored in gear applications. Most existing studies on palm-based lubricants have focused on sliding contacts or journal bearings, with limited attention given to their behavior in gear systems where rolling-sliding contact dominates. The formulation of grease and its application in gear systems remain underexplored, especially in relation to tribological performance under dynamic conditions. This limited focus has created a critical gap in understanding how palm-based greases behave under the specific loading, motion, and contact conditions of gear operation, particularly their effects on wear, vibration, and long-term durability.

To address this gap, the present study involves the fabrication of a custom gear test rig designed to investigate surface wear and vibration characteristics under realistic operating conditions. The rig is integrated with a National Instruments data acquisition system and LabVIEW software to enable real-time monitoring and analysis. A new formulated palm olein-based grease, enhanced with molybdenum disulphide ( $\text{MoS}_2$ ) nanoparticles, is formulated and tested for its tribological performance in spur gears. The primary objective of this study is to evaluate the effectiveness of the formulated grease in reducing wear and vibration, and to compare its performance against a commercial mineral-based grease. This research aims to contribute to the development of sustainable lubrication solutions for gear systems, offering insights into the viability of palm-based greases in industrial applications.

## 2. Methodology

### 2.1 Materials

The formulation of palm olein-based grease involves dispersing a thickening agent into refined, bleached, and deodorised (RBD) palm olein, which serves as the base oil. This process transforms the oil from a liquid into a semi-solid structure. Lithium 12-hydroxystearate, in powdered form, was selected as the thickener, while 0.5 wt.% of molybdenum disulphide ( $\text{MoS}_2$ ) nanoparticles (90 nm) additive was incorporated to improve the grease's tribological properties. The proportions of base oil and thickener were determined through preliminary trials, with the composition demonstrating optimal friction performance selected for testing. Initially, 70% of the total base oil was added to a beaker and heated on a hot plate. Once the target temperature was reached, 13 wt.% of the thickener was gradually introduced while stirring with an overhead stirrer. After complete addition, the mixture was further heated to complete the saponification process, during which the stirrer speed was increased to accommodate the rising viscosity. Subsequently, the temperature was raised further to ensure full dissolution of the thickener, together with the addition of the additive. The remaining base oil was then added while stirring, and the mixture was allowed to cool to promote recrystallisation. Finally, the grease was homogenised to achieve a smooth and uniform texture.

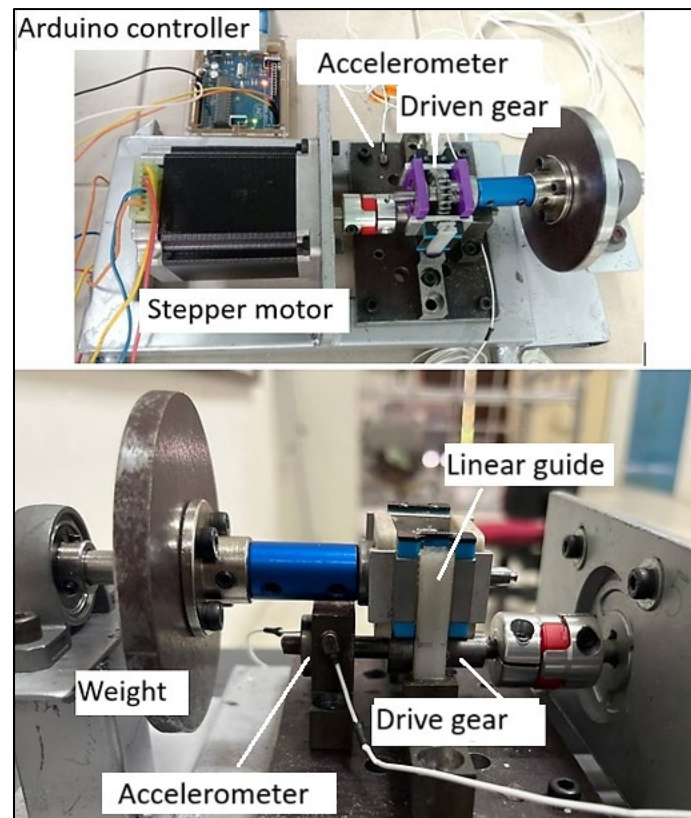
Prior to testing, the viscosity of the palm oil was measured using a viscometer in accordance with the ASTM D445 standard test method. The cone penetration test for the palm-based grease was conducted following the ASTM D217 standard to determine its National Lubricating Grease Institute (NLGI) grade. For performance comparison, two commercially available mineral greases typically used for rolling contact applications were also tested. The properties of all grease base oil used in this study are summarised in Table 1.

**Table 1** Properties of grease lubricants

Properties	Base oil		
	Palm grease (PG)	Mineral grease 1 (MG1)	Mineral grease 2 (MG2)
Viscosity at 40°C (mm <sup>2</sup> /s)	46.76	150–170	110
Viscosity at 100°C (mm <sup>2</sup> /s)	8.91	15	11
Viscosity index	174	95-105	95
NLGI grade	2	2	2
Dropping point (°C)	208	210	≥180°C

## 2.2 Spur Gear Test Rig

Fig. 1 shows a gear test rig fabricated for this study. A pair of spur gears was vertically arranged to form a gear set, with a torque of 0.31 Nm applied to the driven gear. An Arduino UNO was programmed to set a speed of 300 rpm in this experiment. The stepper motor drives the rolling motion of the lower gear, which is designated as the drive gear. This rolling motion is transferred to the upper gear, which is referred to as the driven gear. The motion in the horizontal direction is constrained by a linear guide, which ensures precise alignment of the gear shafts during operation. This constraint is essential for maintaining consistent line contact between gear teeth, as any lateral displacement or misalignment could result in uneven load distribution, increased vibration, and premature wear. Such inaccuracies would compromise the reliability of the test results and obscure the true effects of the grease on gear wear and vibration. The test rig was designed on a small scale, with a system configuration that allows easy dismounting of the gears for surface analysis under a microscope. The properties of the spur gear used in this study are shown in Table 2.



**Fig. 1** Spur gear test rig set up

**Table 2** Specification and material properties of spur gear

Parameters	Values
Pressure angle (°)	20
Material	Steel EN8 (080M40/080M46)
Number of teeth	20
Tooth width (mm), [B]	5
Bore diameter (mm)	6
Hub diameter (mm), [dm]	14
Pitch diameter (mm), [dp]	20
Outer diameter (mm), [de]	22
Tensile strength	550 MPa
Yield strength	280 MPa

## 2.3 Wear Analysis and Surface Characterization

Wear analysis was conducted by measuring the mass loss of the gear. The initial weight of the spur gears was recorded using a weighing scale, and the final mass was measured after 240,000 rotation cycles, during which significant surface wear was observed. The total mass loss was then calculated to determine the reduction in the sample's weight after the experiment. Surface wear characterization was performed using a Hitachi S-3400N Scanning Electron Microscope (SEM) and elemental analysis was further conducted using Energy Dispersive Spectroscopy (EDS). The gear surface was initially scanned at 20 $\times$  magnification at the meshing teeth area as illustrated in Fig. 2. The magnification was then increased to 100 $\times$  for a more detailed observation of surface damage and wear. Measurements were performed at several different locations to assess the wear characteristics across the entire surface.

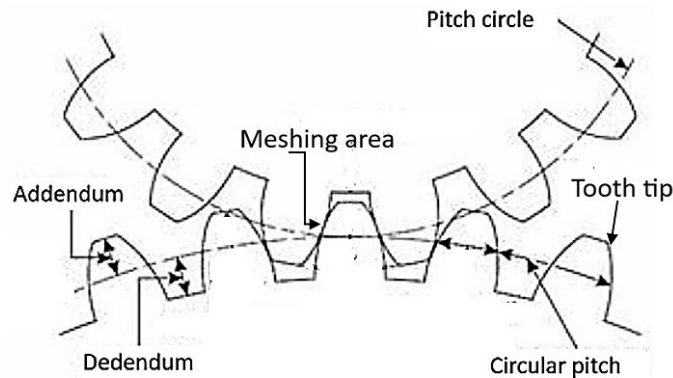


Fig. 2 Gear surface scanning at the teeth meshing area

## 2.4 Vibration Data Acquisition

Vibration analysis was conducted using LabVIEW software. A Data Acquisition (DAQ) device from National Instruments was connected to a computer running the software. Two accelerometers with a sensitivity of 2.5 mV/g were mounted on the gear test rig to collect vibration data. In LabVIEW, a basic program was implemented to process the vibration data using Fast Fourier Transform (FFT). Each dataset collected by the accelerometers was analyzed in both the time and frequency domains. A total of 20,000 datasets were recorded at a sampling rate of 10,000 Hz. Measurements were performed at least three times to confirm the values, and were taken in both the vertical and horizontal directions relative to the gear mounting. Gear mesh frequency (GMF) and its harmonics were observed during the measurement, as this parameter plays a crucial role in detecting gear defects through vibration analysis. GMF is defined as the rate at which gear and pinion teeth periodically engage. A faulty gearbox typically generates high vibration at this frequency, making GMF a highly effective parameter for vibration analysis. GMF is calculated as the product of the shaft rotation speed and the number of gear teeth.

## 3. Results and Discussion

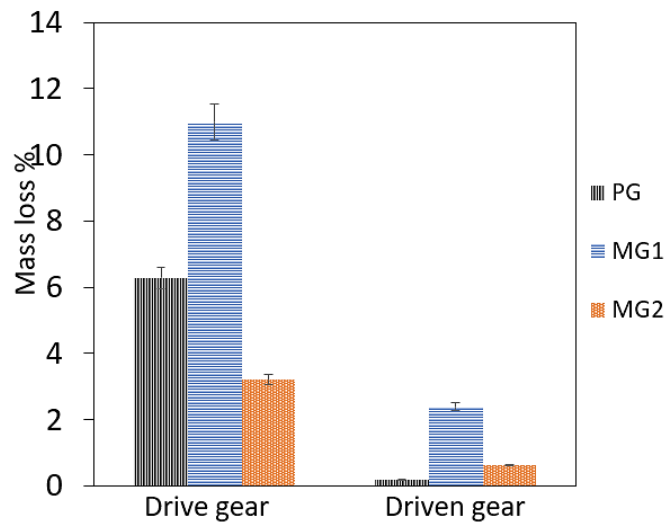
### 3.1 Wear Analysis

#### 3.1.1 Gear Mass Loss and Roughness Analysis

The mass loss of the gear was measured to quantify material removal from the gear teeth due to wear. Table 3 presents the mass loss analysis for the drive and driven gears after the experiment and the percentage of mass loss is illustrated in Fig. 3. The initial and final masses were recorded, and the percentage of mass loss was calculated for all greases. Overall, the mass loss of the drive gear was significantly higher than the driven gear. Among the drive gears, the gear lubricated with MG2 exhibited the lowest mass loss at  $3.20 \times 10^{-2}$  %, indicating minimal wear compared to the others. The gear lubricated with PG showed a slightly higher mass loss of  $6.28 \times 10^{-2}$  %, while the highest mass loss was recorded for the gear lubricated with MG1, at  $10.99 \times 10^{-2}$  %, demonstrating the failure of this grease in surface wear protection. For driven gears, the lowest mass loss was recorded on PG with  $0.19 \times 10^{-2}$  %, followed by MG2 at  $0.62 \times 10^{-2}$  % and MG1 at  $2.39 \times 10^{-2}$  %. This finding indicates that the formulated PG successfully formed a protective lubricating film between the drive and driven gears, enabling efficient energy transfer and reducing friction-induced wear and material loss on the driven gear. This study confirms the effectiveness even at higher cycles, extending previous work in which gears tested at lower cycles showed that reinforcing palm-based grease with nano MoS<sub>2</sub> effectively reduces mass loss with  $0.6 \times 10^{-2}$  % at 40,000 cycles [38].

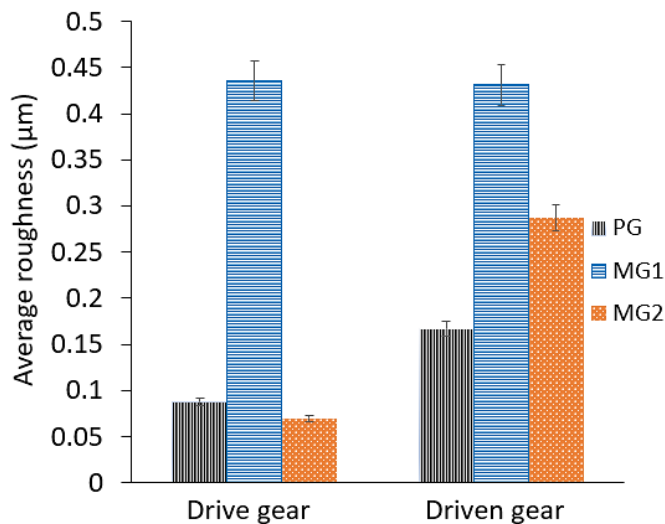
**Table 3** Mass loss analysis of gears

Grease	Drive Gear			Driven Gear		
	Initial (mg)	Final (mg)	Percentage ( $\times 10^{-2}\%$ )	Initial (mg)	Final (mg)	Percentage ( $\times 10^{-2}\%$ )
PG	15.9341	15.9241	6.28	15.9524	15.9521	0.19
MG1	16.0988	16.0811	10.99	16.2298	16.2259	2.39
MG2	15.9320	15.9269	3.20	16.1981	16.1971	0.62



**Fig. 3** Percentage of gear mass loss

The surface roughness average (Ra) of the gears is presented in Fig. 4. Grease MG1 exhibited the highest surface roughness on both the drive and driven gears, with values approaching  $0.44\ \mu\text{m}$ . This indicates that MG1 provided the least effective surface protection, likely due to inadequate film formation under operating conditions. This can be related to the high mass loss recorded for this type of grease, as was discussed in Fig. 3. In contrast, PG showed moderate roughness on the drive gear, with a slight increment in the driven gear differing by approximately  $0.07\ \mu\text{m}$ , suggesting a relatively balanced tribological response across gear contacts. The application of nanoparticle additives in machining lubricants has also been found to improve performance by reducing surface roughness [39]. The surface lubricated with MG2 resulted in the lowest surface roughness on the drive gear; however, a notably higher roughness was observed on the driven gear. This discrepancy may be due to insufficient lubricant film formation or suboptimal energy transfer across the gear mesh, leading to ineffective surface protection under dynamic contact conditions.

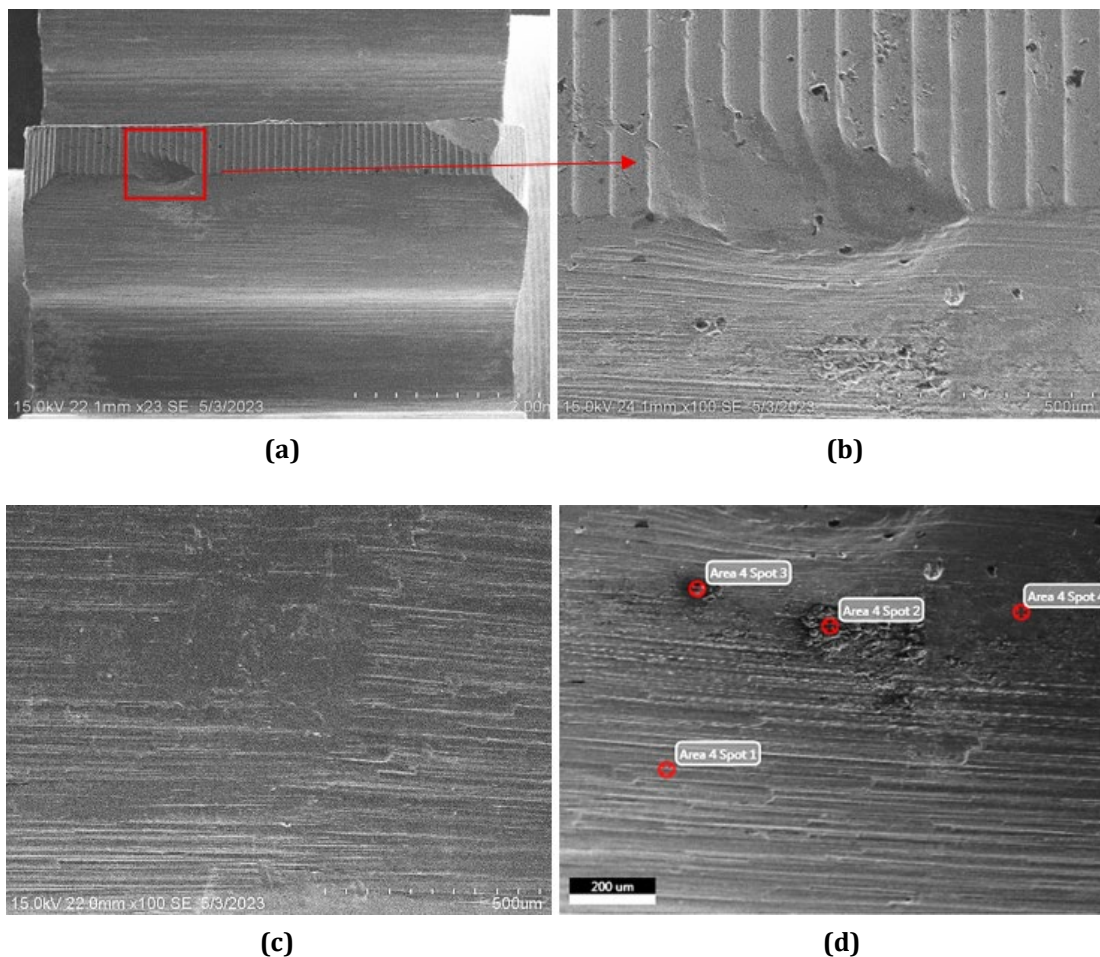


**Fig. 4** Average roughness of the gear

While comparing the mass loss and roughness, the driven gear exhibited significantly lower mass loss than the drive gear, yet showed higher surface roughness. This can be attributed to the differing load dynamics and contact conditions between the two gears. The drive gear, which actively transmits torque, experiences greater contact pressure and material removal through adhesive or abrasive wear, typically resulting in more uniform wear and a smoother worn surface. In contrast, the driven gear is more susceptible to micro-slip or partial sliding during meshing cycles, which can cause surface abrasion and roughening without substantial material removal. It is expected that wear debris generated from the drive gear may become embedded in the contact region of the driven gear, increasing surface roughness through third-body abrasion rather than contributing to mass loss. Additionally, variations in lubrication, such as a thinner lubricant film or less effective replenishment on the driven gear, potentially further enhance asperity contact and surface texture changes without significantly affecting weight loss.

### 3.1.2 Surface Wear Characterization

Surface micrograph of gears lubricated with PG after 240,000 cycles is shown in Fig. 5. Wear dents are observed on the gear tooth tips in Figs. 5(a) and (b). The contact between two gear teeth begins when a lower point on the driving gear's tooth makes contact with the tip of the driven gear's tooth [40]. This is the reason why the gear tips experience severe wear, primarily due to the high localized stress concentrated during initial contact. Further analysis at 100x magnification in Figs. 5 (c) and (d) reveals signs of adhesive and abrasive wear in the addendum area. As the gears rotate, the contact point shifts along the line of action, where the contact moves from the base to the tip on the driving gear's tooth and from the tip to the base on the driven gear's tooth [40]. This causes the surface wear to occur along the gear tooth meshing area, including the addendum area. Elemental analysis was conducted at several spots to evaluate the elemental composition of the worn areas, as shown in Table 4. Iron (Fe) dominated the elemental composition, representing the EN8 steel used for the gears.



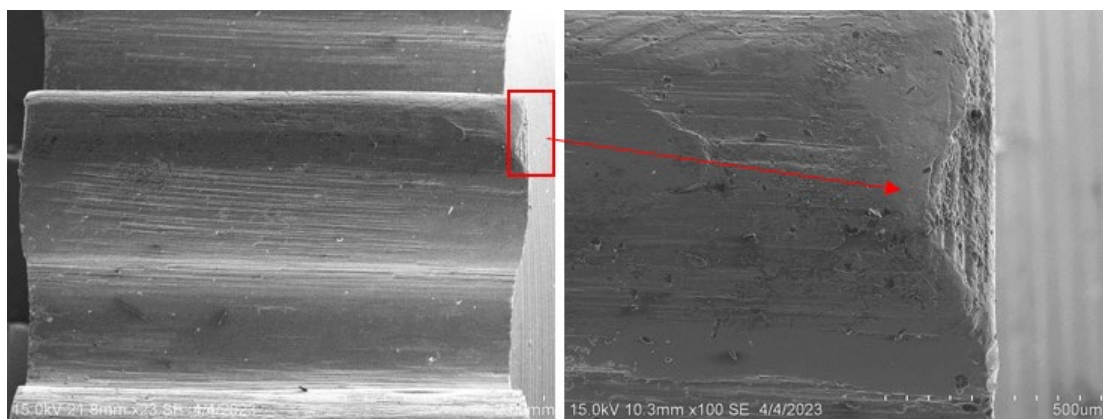
**Fig. 5** Surface micrograph of the gear lubricated with PG (a) and (b) Gear tooth tips; (c) and (d) Addendum and dedendum area

**Table 4** Elemental analysis of the gear lubricated with PG

Element	Weight %			
	Spot 1	Spot 2	Spot 3	Spot 4
C K	13.66	18.97	24.99	6.47
SiK	2.80	0	2.36	0.91
P K	2.09	0	0.84	0.53
MoL	3.16	0	1.54	1.45
S K	0.10	0	0.05	0.07
MnK	5.34	1.66	3.28	5.72
Fe K	72.39	79.36	66.94	80.09

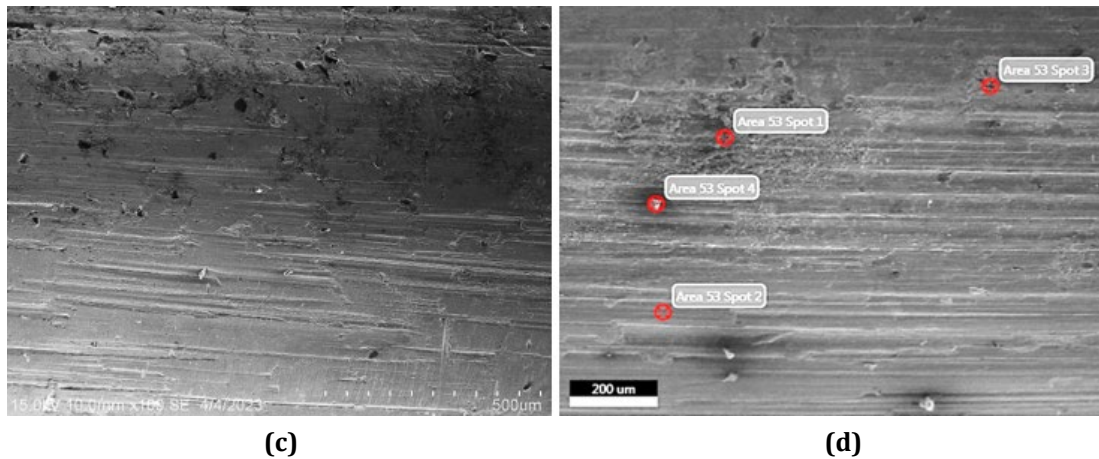
According to the material datasheet, carbon (C), silicon (Si), phosphorus (P), manganese (Mn), and sulfur (S) are alloying elements in EN8 steel, each present at less than 1%. The high carbon content found on the surface is likely due to the presence of fatty acid elements in the palm oil content. Molybdenum (Mo) was detected at three spots, with concentrations of up to 3.16%, originating from the  $\text{MoS}_2$  additive in palm grease. The presence of the Mo element is primarily due to the small size of  $\text{MoS}_2$  nanoparticles, which allows them to easily enter the interface between contacting surfaces. Their presence helps to reduce wear severity by forming a protective layer that limits further material loss. This behavior is also consistent with the mending effect mechanism, where the nanoparticles accumulate in worn regions and contribute to surface restoration [27]. Lubricants containing nanoparticle additives contribute to wear surface enhancement through mending and surface polishing mechanisms [24]. The mending effect of nanoparticles is attributed to their tendency to deposit on interacting surfaces, compensating for mass loss [25]. At Spot 2, rough surfaces were observed with signs of material accumulation. High Fe and C content suggests the accumulation of metal wear particles on the surface. Spot 3, which appears darker, exhibits a high carbon concentration.  $\text{MoS}_2$  nanoparticles may form tribo-films through aggregation in the contact zone. These films enhance lubrication and may interact with palm oil components, potentially incorporating carbonaceous materials.

Fig. 6(a) displays sliding marks along the contact direction on a gear lubricated with MG1, with a worn area at the tooth tip edge highlighted by the red box. Fig. 6 (b) provides a magnified view of this region, revealing localized wear and severe material degradation. Further scanning at higher magnification revealed the presence of scratch marks and micro-pitting in the addendum area, as shown in Figs. 6 (c) and (d). This type of defect may result from the lubricant's inability to form a uniform protective layer, as well as external factors such as misalignment. Micro-pitting is a form of rolling contact fatigue that occurs on a microscopic scale due to concentrated stress in localized areas near the contacting surfaces [34]. It is typically found between the pitch line and the tooth root. Micro-pitting can result not only from mechanical issues but also from chemical interactions, where lubricant additives react with the surface, potentially leading to stress-induced cracking or the formation of a reaction layer [41]. These reactions contribute to the development of tiny cracks in the shallow surface layer of the material. Elemental analysis in Table 5 shows a similar elemental composition to the PG lubricant, but with the absence of Mo. This further validates that the Mo element in the  $\text{MoS}_2$  additive was absorbed on the lubricated surface in the PG sample.



(a)

(b)

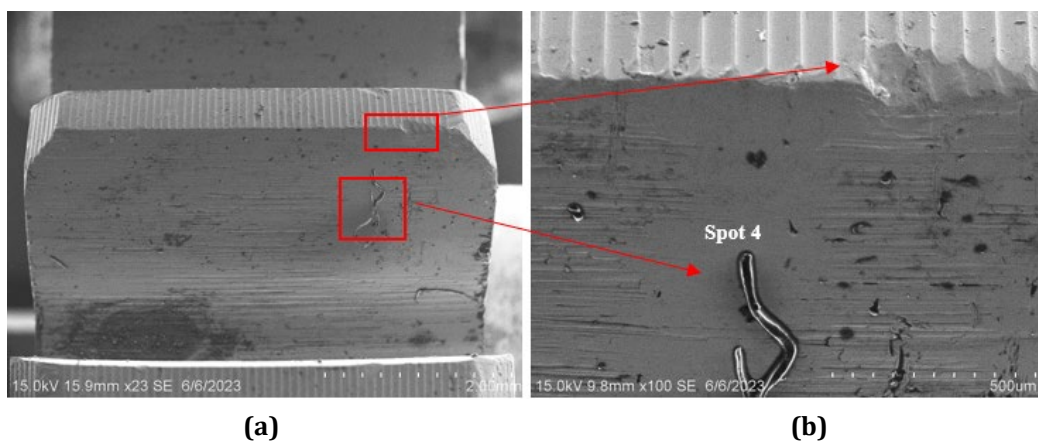


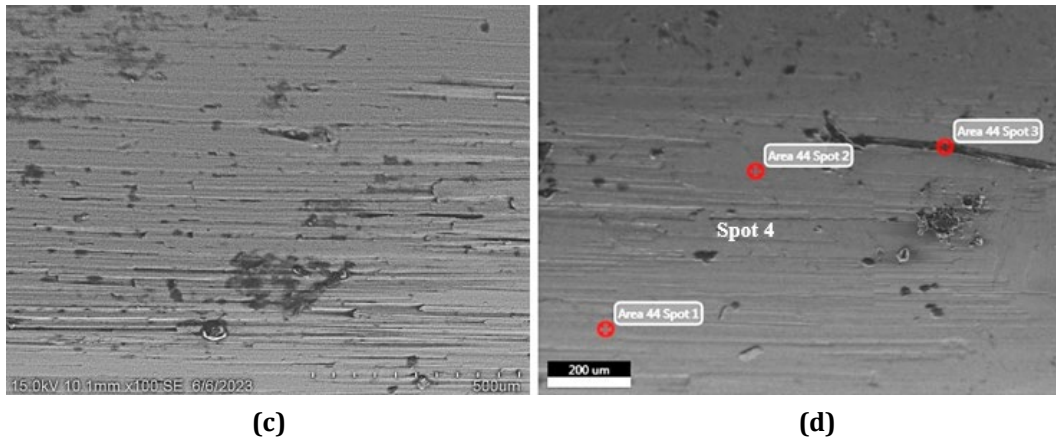
**Fig. 6** Surface micrograph of the gear lubricated with MG1 (a) and (b) Gear tooth tips; (c) and (d) Addendum and dedendum area

**Table 5** Elemental analysis of the gear lubricated with MG1

Element	Weight %			
	Spot 1	Spot 2	Spot 3	Spot 4
C K	19.16	16.92	2.45	25.7
SiK	1.07	0	0.28	0.31
P K	2.17	2.21	0.10	0.43
MoL	0	0	0	0
S K	0.03	1.20	0.04	0.81
MnK	3.43	4.91	8.26	4.70
Fe K	74.13	72.9	88.86	68.06

Additionally, elemental analysis at spot 1 and spot 4, which exhibit a rougher and darker appearance, indicates a high carbon content, possibly originating from hydrocarbons in the mineral oil. Spot 1 also shows signs of abrasive wear, which typically occurs across the entire width of the tooth face due to material removal from gear teeth. The sliding contact produces wear particles that contaminate the gear system and affect the gear tooth's geometric profile [42]. Fig. 7 (a) shows a surface micrograph for gear lubricated with MG2 grease. A surface dent was observed on the gear tooth tip and material chips were found near the scratch area, as shown in Fig. 7 (b). It is expected that these material chips were removed from the gear surface and acted as third bodies between the contacting surfaces, leading to third-body abrasion. The presence of microchips on the surface is likely due to surface hardening, as the high carbon content increases the tendency for the material to fracture. Further scanning at higher magnification in Figs. 7 (c) and (d) revealed shallow furrows on the surface aligned with the sliding or movement direction.





**Fig. 7** Surface micrograph of the gear lubricated with MG2 (a) Gear tooth tips; (b) Material chip; (c) and (d) Addendum and dedendum area

Elemental analysis at spots 1 and 2, where the surfaces appear cleaner and smoother, shows that Fe and C are the dominant elements, as presented in Table 6. The detection of Mo indicates the presence of a molybdenum-based additive in this mineral grease. Analysis of the material chip observed at spot 4 indicates a high carbon and oxygen content. This could be attributed to frictional heating during sliding, which causes oxidation and leads to the formation of metal oxides [43]. Another possible reason is the breakdown of hydrocarbon-based oils in mineral grease under extreme temperature or pressure conditions [44], resulting in the formation of carbonaceous residues. Additionally, the decomposition of additives with molybdenum element under boundary lubrication conditions can lead to the formation of carbon and oxygen-rich tribo-films, which act as protective layers on metal surfaces [45]. The MG2 grease is expected to promote carbon formation on the surface for enhanced protection, while the increased carbon content contributes to improved hardness and strength.

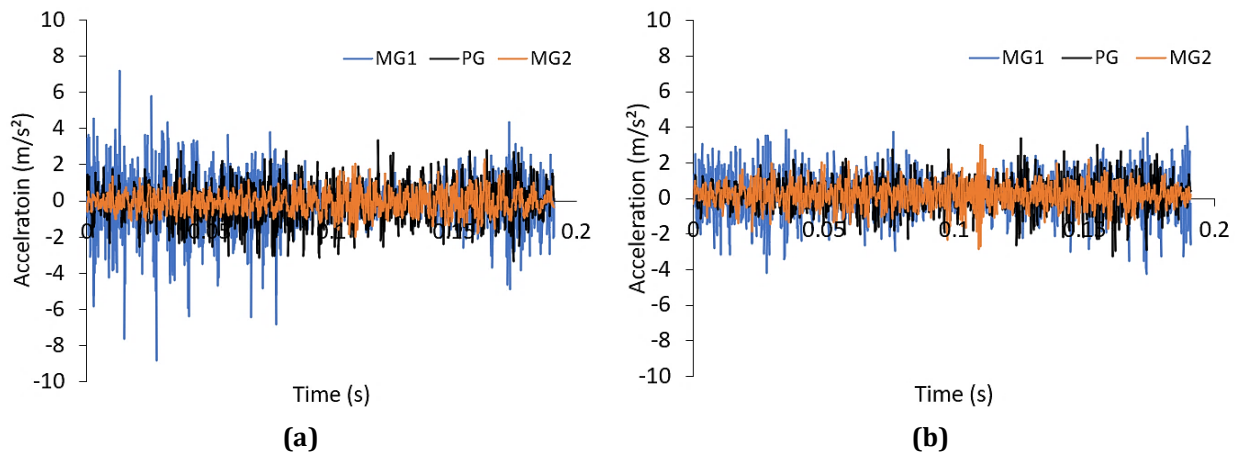
**Table 6** Elemental analysis of the gear lubricated with MG2

Element	Weight %			
	Spot 1	Spot 2	Spot 3	Spot 4
C K	40.86	39.55	66.26	55.57
SiK	1.55	1.17	0	0.51
P K	0.58	0.17	0	0.15
MoL	0.95	0.61	0.14	0.20
S K	0.01	0.07	0	0
MnK	2.31	2.05	0.19	0.47
Fe K	53.74	50.38	0.72	7.86
O K	0	0	32.69	35.07

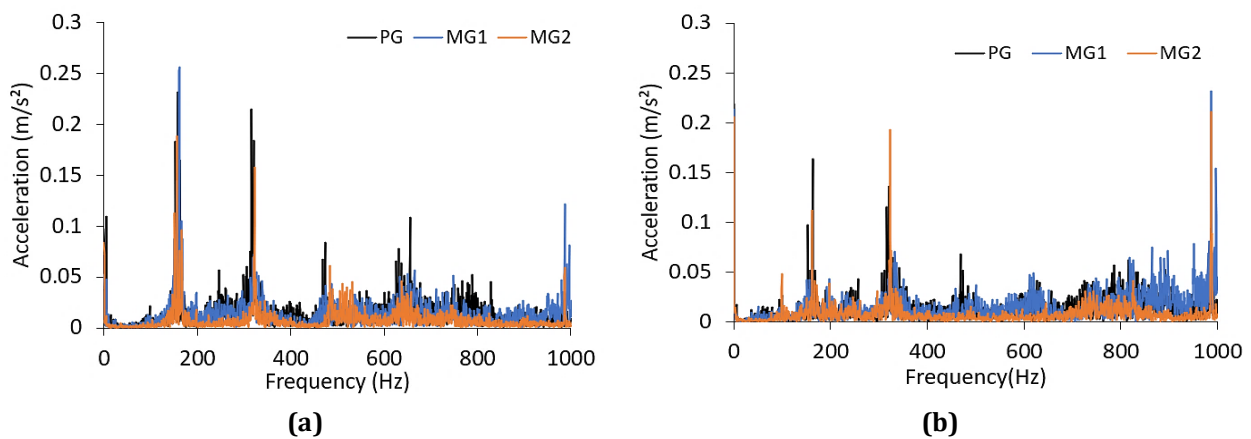
### 3.2 Vibration Analysis

The vibration response of the gears lubricated with all greases in the time and frequency domains is shown in Figs. 8 and 9, respectively. In general, vibration in the vertical direction is higher than in the horizontal direction. Fig. 8 shows that MG2 grease exhibits the highest acceleration values in both vertical and horizontal directions, followed by PG and MG1. The formulated palm-based grease demonstrates a moderate vibration level, remaining within an acceptable range compared to commercially available grease. This suggests that the grease has the potential to minimize vibration during gear operation. When compared with the surface characterization in Fig. 6, scratches and micro-pitting were observed on the surface. The high vibration could be attributed to mechanical interactions between the surfaces, possibly due to the grease failing to form a sufficient protective layer. Additionally, EDS analysis did not detect any additive elements that could enhance the grease properties. The vibration spectra of the gear, as shown in Fig. 9, reveal high vibration amplitudes at the gear mesh frequency (GMF) and its harmonics. The vibration amplitude follows a consistent pattern with the time-domain plot, with the highest amplitude occurring at the GMF for MG2, followed by PG and MG1. The elevated vibration amplitude at the GMF can be attributed to surface wear, as observed in the earlier surface micrograph analysis. Surface

defects such as dents, scratches, and micro-pitting are likely contributing factors to the increased vibration response, particularly for MG2 grease.



**Fig. 8** Vibration analysis of the gear in time domain for (a) Vertical axis; (b) Horizontal axis



**Fig. 9** Vibration analysis of the gear in the frequency domain (a) Vertical axis; (b) Horizontal axis

The recorded vibration amplitudes at the GMF are presented in Fig. 10. In the vertical direction, MG1 exhibited the highest vibration level at approximately  $0.9 \text{ m/s}^2$ , followed by PG at  $0.7 \text{ m/s}^2$ , while MG2 demonstrated the lowest vibration at around  $0.55 \text{ m/s}^2$ . A similar trend is observed in the horizontal direction, where MG1 again recorded the highest vibration at  $1.0 \text{ m/s}^2$ , PG showed a moderate level at  $0.8 \text{ m/s}^2$ , and MG2 had the lowest level at  $0.45 \text{ m/s}^2$ . These results suggest that MG2 offers superior vibration damping performance compared to the other greases, likely due to its rheological properties or film-forming ability that reduces gear mesh impact. In contrast, MG1, despite being a mineral grease, resulted in the highest vibration levels in both directions, indicating potentially lower damping efficiency or poorer film stability under dynamic loading. The overall vibration levels of the formulated palm oil-based grease (PG) fall within an intermediate range between mineral greases MG1 and MG2. The consistent performance of PG, with moderate vibration in both axes, suggests stable gear lubrication but with slightly less damping capacity than MG2. An increase in gear surface wear leads to higher amplitudes of the fundamental gear mesh frequency and its corresponding harmonics in the vibration spectrum. These findings suggest that the formulation of PG, incorporating palm olein and  $\text{MoS}_2$  nanoparticles, has the potential to serve as an effective lubricant in gear applications.

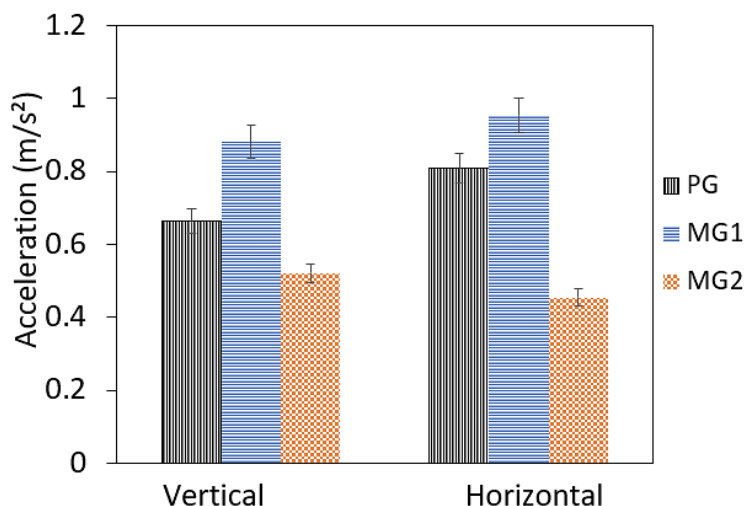


Fig. 10 Vibration analysis at the gear mesh frequency

#### 4. Conclusions

A palm oil-based grease was successfully formulated using a lithium thickener and MoS<sub>2</sub> nanoparticles additive. The grease was tested using a spur gear test rig, surface wear characterization, elemental analysis, and vibration measurement were conducted to evaluate its performance. Wear analysis indicates that the developed palm grease has a comparable performance to commercial mineral grease MG2 and outperforms MG1 with less surface wear and material loss. Surface characterization reveals that the gear lubricated with MG1 exhibits more scratches and micro-pitting, whereas MG2 shows a mix of smooth regions and minor furrows, along with the presence of material chips. The presence of MoS<sub>2</sub> was detected on the surfaces lubricated with PG and MG2, indicating that the additive contributed to the formation of a protective layer. In contrast, no Mo element was observed on the surface lubricated with MG1, which explains its lower protective performance. The incorporation of MoS<sub>2</sub> nanoparticles into the palm-based grease demonstrates significant tribological benefits, while the small particle size enables effective penetration into the gear contact interface, contributing to the formation of a protective tribo-film that mitigates wear and material loss.

The vibration results aligned with the surface characterization findings, where MG2 exhibited the highest acceleration values in both vertical and horizontal directions, followed by PG and MG1. Overall, the results suggest that the formulated palm oil-based grease with MoS<sub>2</sub> nanoparticles has the potential to serve as an effective lubricant in gear applications, providing surface protection and reducing wear. This performance enhancement highlights the engineering potential of the developed grease in reducing component degradation under dynamic conditions. Furthermore, the use of a biodegradable palm oil base aligns with environmental sustainability goals, offering a promising alternative to conventional mineral-based greases in industrial applications.

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#### Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

#### Author Contribution

The authors confirm contribution to the paper as follows: **data collection, analysis and interpretation of results:** A. A. Hasan; **grease, data acquisition setup and test rig preparation:** N.A. Abdullah; **rig design, analysis and draft manuscript preparation:** N.F.M. Yusof. All authors reviewed the results and approved the final version of the manuscript.

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