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Tribological enhancement of modified jatropha oil by activated carbon nanoparticle for metalworking fluid application

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KEYWORDS

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ABSTRACT

The excessively use of petroleum-based oil as a metalworking fluid is hazardous to the worker and cause a pollution to the environment. As a result, environmentally friendly oil has gradually replaced petroleum-based oil in the machining process. The goal of this study is to investigate the tribological enhancement of modified jatropha oil (MJO) by activated carbon nanoparticle (AC) ranging from 0.01 to 0.05 wt.% through the four-ball test and turning process. The results reveal that MJO with 0.025wt% AC nanoparticle has exceptional tribological performance in terms of friction and wear, resulting in extended tool life in terms of machining length (7000mm) and machining time (49 minutes). The addition of 0.025wt.% AC nanoparticle created a protective layer that facilitates rolling action at the sliding surfaces. As a result, MJO with 0.025wt% AC has excellent tribological properties, making it a viable alternative as an environmentally friendly metalworking fluid.

1.0 INTRODUCTION

Tribological performance in lubrication is the study of controlling and managing lubricity, friction, and wear. The interfacial friction within the sliding system phenomena is a process that is continually accompanied by the change of energy form, where moving two objects together with the condition that both of them are in motion certainly dissipates the energy as it is the phenomenon of friction (Chan et al., 2018). Lubricants are primarily used to lubricate machines

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and materials in order to reduce friction, minimize wear, release heat, remove impurities, and improve efficiency between two contact surfaces (Paras et al., 2019). Friction arose between tool and workpiece which altered the surface quality during the machining process.

Straight oil is one of the major oils used as metalworking fluid. Straight oils were not intended to be diluted in any way. Workers were exposed to MWFs by inhaling aerosols and dermal contacts with the fluid. The amount of exposure depends on the application process. Skin problems are common among workers who may be exposed to MWFs. The list of industries with the greatest prevalence of skin problems in 1991 (for example, fabricated, screw machine goods, and general industrial machinery) all entailed possible MWF exposure (NIOSH, 1998). Furthermore, the use of petroleum-based oil also causes environment pollution. Petroleum refineries are a significant source of harmful and toxic air pollutants including BTEX chemicals (benzene, toluene, ethylbenzene, and xylene). They are also a significant producer of particulate matter (PM), nitrogen oxides (NO_x), carbon monoxide (CO), hydrogen sulphide (H_2S), and Sulphur dioxide (SO_2)(Hazardous Substance Research Center, 2003).

Due to the problem, vegetable oil has gained widespread recognition as a lubricant because of its superior renewable, biodegradable, and technological properties. Vegetable-based oils have a greater viscosity index, which provides better lubricity across a wider temperature (Kuram et al., 2013). Vegetable oil viscosity reflected its oiliness and fluidity, with higher viscosity typically resulting in better film strength and fluidity (Guo et al., 2017).

Currently, jatropha oil has the potential to replace petroleum-based oil because it is abundantly available. Jatropha oil is a non-edible vegetable oil that has excellent lubricating characteristics. According to Talib et al. (2017), crude jatropha oil (CJO) exhibits poor lubricating behavior due to low thermal-oxidative stability, which necessitates oil modification to improve its qualities. As a result, (Masood et al., 2012)concluded that chemical modification of oil is the greatest method for improving the performance of vegetable oils. According to (Abdul Sani et al., 2017), the modified jatropha oil had a significant impact on the tribological performance of metal sliding pairs in the four-ball wear test and tapping torque test in terms of enhanced wear and friction reduction. While (Talib & Rahim, 2016) demonstrated that the modified jatropha oil can generate a thin lubricating coating that can resist friction at the cutting tool-workpiece contact, resulting in lower cutting forces and temperatures.

Recently, the existence of nanoparticles in the metalworking fluid known as a nanofluid contributed to the enhanced flow of mixing and an increase in thermal conductivity contrary to the neat fluid (Azwadi et al., 2017). Nanoparticles have long been utilized to improve lubricant tribological characteristics. The frictional behavior of nanoparticles is significantly influenced by their mechanical interaction , whereas the anti-wear behavior is mostly influenced by their chemical interaction (Mushtaq & Hanief, 2021). (Begum et al., 2019) stated that the combination of vegetable oil with nanoparticles produced a better lubricant that provides a protective layer between the contact surfaces. Despite this, the addition of nanoparticles offers a rolling effect at the mating surfaces that transformed sliding friction into both sliding and rolling friction thus affecting the reduction of friction. Talib et al. (2019) found that the performance of the modified jatropha oil in combination with hexagonal nitride particle nanoparticles through the orthogonal cutting process formed tribo-films by depositing the nanoparticles at the contact surfaces. This result is parallel to finding from previous work from (Singh et al., 2017) which stated that the additional nano-sized particles obtain good stability of the oil. The use of nano-enriched metalworking fluid significantly reduced the cutting force and workpiece surface roughness.

In the meantime, according to (Radhiyah & Jun Li, 2020), the usage of activated carbon (AC) as a lubricant additive demonstrates exceptional improvement toward the base oil by enhancing the adsorptive qualities. AC has a porous structure and chemical capabilities on the surface that help it promote non-polar and polar adhesion (Oginni et al., 2019). According to (Rodriguez-Reinoso & Silvestre-Albero, 2016) the effectiveness of AC is determined by the surface chemistry of carbon, which plays a significant influence in AC's adsorptive characteristics. Therefore, in this study, the tribological performance of modified jatropha oil (MJO) with the addition of AC nanoparticles was investigated through a four-ball test and turning process, and the results were compared to pure MJO and synthetic ester (SE). This new oil formulation may open up more possibilities for machining operations, especially when it comes to the use of metalworking fluid.

2.0 EXPERIMENTAL METHODS

2.1 Preparation of Metalworking Fluids

The chemical alteration of crude jatropha oil (CJO) was the first step in the production of modified jatropha oil (MJO). CJO goes through a two-step acid-based catalytic process to generate jatropha methyl ester (JME). Following that, MJO was created by trans esterifying trimethylolpropane ester (TMP) with JME at a ratio of 3.5:1 with 1 percent (wt./wt.) sodium methoxide ($NaOCH_3$) (Jamaluddin et al., 2020a). The suitable TMP for metalworking fluid is TMP that produced higher percentage of TMP ester (Sripada et al., 2013). Bamboo activated nanoparticles (size <100 nm) were employed as an additive because they had a high organic component removal capacity and were cost-effective with superior lubricating performance. The physical parameters of activated carbon are listed in Table 1. MJO was blended with AC nanoparticles in various concentration ratios (0.01, 0.025, and 0.05 wt.%) to form the MJO nanofluids using a magnetic stirrer at 700 rpm and a temperature of 60°C for 30 minutes.

Table 1: Physical properties of AC nanoparticle additives (Talib et al., 2021).

Properties	Description
Appearance	Black powder
Density (g/cm^3)	3.3
Size (nm)	50
Melting point (°C)	1772
Solubility in water	Insoluble
Thermal expansion coefficient (K^{-1})	3.6×10^{-6}

This process was to make sure AC nanoparticle distribute well in MJO. The sample was observed over time to evaluate the dispersion stability by using sedimentation method. As the density of AC is higher than MJO, AC tend to sediment over time. However, the dispersion of AC in MJO considered a good dispersion stability as during observation, there are no obvious sedimentation over a short time.

2.2 Four-Ball Test

The tribology testing was done with a four-ball tribotester, the DUCOM TR-30L, which was based on ASTM D4712. Each test employed four steel balls made of AISI 52100 with a hardness of 64 to 66 HRC and a diameter of 12.7 mm. 10 ml of oil sample was inserted into the ball port.

The three stationary balls were clamped in the ball pot assembly. The rotating ball was placed into the collet and was squeezed inside the spindle. The ball port was installed in the tribotester machine, and a normal load of 392±2N was gradually introduced to avoid any extreme stress. The oil heating temperature was set at 75±2°C. The rotating ball was run at a continuous speed of 1200rpm for 60 minutes after achieving the requisite temperature. The coefficient of friction (COF) was calculated using Winducom software based on the results of the tests. The mean wear scar diameter (MWSD) of the stationary steel balls was measured using a scanning electron microscope (SEM, Toshiba S-3000N).

2.3 Turning Process

The modified jatropha oil (MJO) sample that showed the best performance in the tribology test was proceeded with the turning process and was compared to SE. AISI1045 steel with a 150mm diameter and an uncoated cermet cutting tool has been used in this experiment using NC Harrison Alpha 400. A constant cutting speed of 300m/min, a feed rate of 0.2mm/rev, and a depth of cut of 1mm was used as the machining parameter. The metalworking fluid was supplied using the minimum quantity lubrication (MQL) method. At 500mm cutting length intervals, a Nikon MM-60 tool maker microscope was utilized to assess the wear development at the flank face for average flank wear (V_{BB}), maximum flank wear (V_{BBmax}), and notch wear (V_{BN}). The tool's life was measured when a tool failed and surpassed the tool wear requirements based on ISO3685 standards as shown in Table 2. The total machining time (min) and total cutting length (mm) were used to calculate the tool life. Tool wear at the flank face was examined through a scanning electron microscope (SEM, Toshiba S-3000N) equipped with energy-dispersive X-ray spectroscopy (EDX).

Table 2: The tool life criteria based on ISO3685.

Type of wear	Parameter
Average flank wear, V_{BB}	≥ 0.3 mm
Maximum flank wear, V_{BBmax}	≥ 0.6 mm
Maximum notch wear, V_{BN}	≥ 0.6mm

3.0 RESULTS AND DISCUSSION

3.1 Coefficient of Friction and Mean Wear Scar Diameter

The tribological behavior of coefficient of friction (COF) and mean wear scar diameter (MWSD) of the researched lubricant samples was shown in Figure 1 and Figure 2. In comparison to synthetic ester (SE), the modified jatropha oil (MJO) nanofluids have outstanding tribological characteristics. MJOs show improvement in COF from range 13.5 % to 59.6 % and enhancement in MWSD from 28.4% to 51.4 %. SE has a low viscosity index, which results in higher flow resistance and caused an increase in COF and MWSD (Talib et al., 2019;2021). The lower viscosity index of SE produce unstable lubrication and viscosity across range of temperature (Ab. Latif et al., 2019). In addition, MJOs form a stronger lubrication film due to the creation of a long molecular chain and branched in MJOs resulting in better COF and MWSD (Rahim et al., 2017). In particular, the polar functional groups in fatty acid molecules in the MJOs sample contribute to their capacity to securely bond to the surface of the metal (Lubis et al., 2017). Moreover, the polar carboxyl group was tightly packed and developed a strong lubricating film which was sufficient to reduce friction(Kashyap & Harsha, 2016).

Besides that, from the graph in Figure 1, MJO+0.01wt.% AC, MJO+0.025wt.% AC, and MJO+ 0.05wt.% AC shows improvement in terms of COF by 65%, 74.3% and 65.7% respectively compared to MJO. In addition, there was a decrement of 24.4%, 32% and 29.3% in MWSD relative to MJO for MJO+0.01wt.% AC, MJO+0.025wt.% AC, and MJO+0.05wt.% AC respectively in Figure 2. The result shows that the COF and MWSD of MJOs improved with the addition of activated carbon nanoparticle additives. This was due to the reduction of contact pressure when nanoparticles occupied the valleys on the surfaces and resulted in the sliding friction altered to a rolling effect in the contact region (Jamaluddin et al., 2020b; Talib et al., 2021). In addition, the nanoparticles react with the oil and the surrounding environment to develop a protective coating between the sliding surfaces, preventing metal-to-metal contact. (Mushtaq & Hanief, 2021). Furthermore, in previous study of Jamaluddin et al. shows the addition of hexagonal boron nitride (hBN) and graphene nanoparticle to MJO respectively give the improvement in COF and MWSD (Jamaluddin et al., 2020b, 2020a). It shows the same trend of result with this study. Which in this study, Activated Carbon was added to MJO and exhibited better COF and MWSD compared SE and MJO itself. It can be concluded that the result for COF and MWSD can be improved with the addition of nanoparticles to the MJO.

Between the MJOs with varied concentrations of activated carbon, MJO + 0.025 wt.% of AC delivered the best COF (0.036) and lowest MWSD (457.63μm). According to current study of Talib et al. (2021), the result for COF and MWSD of MJO with AC also convey the same trend, which MJO + 0.025 wt.% of AC achieved the lowest COF and MWSD. The presence of an adequate concentration of nanoparticles converts the sliding friction to rolling friction in the contact area as illustrated in Figure 3(b), hence lowering the COF (Talib et al., 2018). On the other hand, the addition of 0.01 wt.% and 0.05 wt.% of activated carbon nanoparticles to the MJO led to poor tribological behavior. MJO + 0.01 wt.% of AC produced an inadequate protective layer between the contact surface as shown in Figure 3(a). Thus, it increases the exposed area resulting in a rise of COF and greater MWSD (Talib et al., 2021). Furthermore, the addition of 0.05 wt.% of AC nanoparticles generated particle agglomeration as illustrated in Figure 3(c), which had a significant impact on the lubricant's quality. The lubricating film thickened as a result of the relatively large concentration of additional nanoparticles, increasing the COF and MWSD (Padmini et al., 2016; Talib et al., 2021).

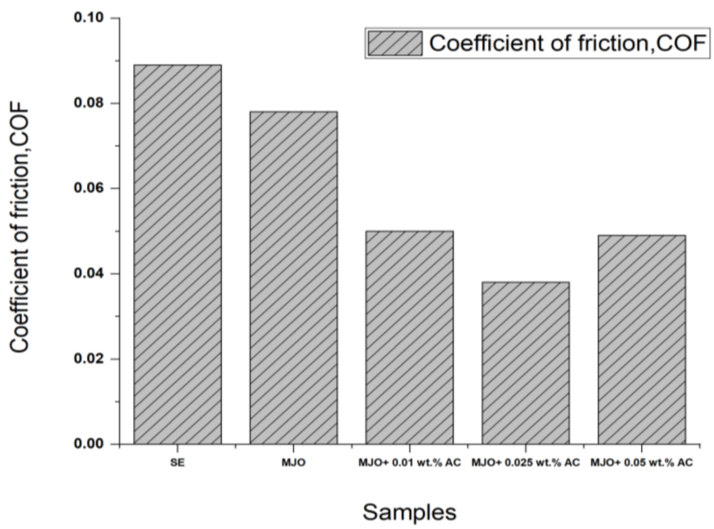


Figure 1: Graph of coefficient of friction (COF) for all samples.

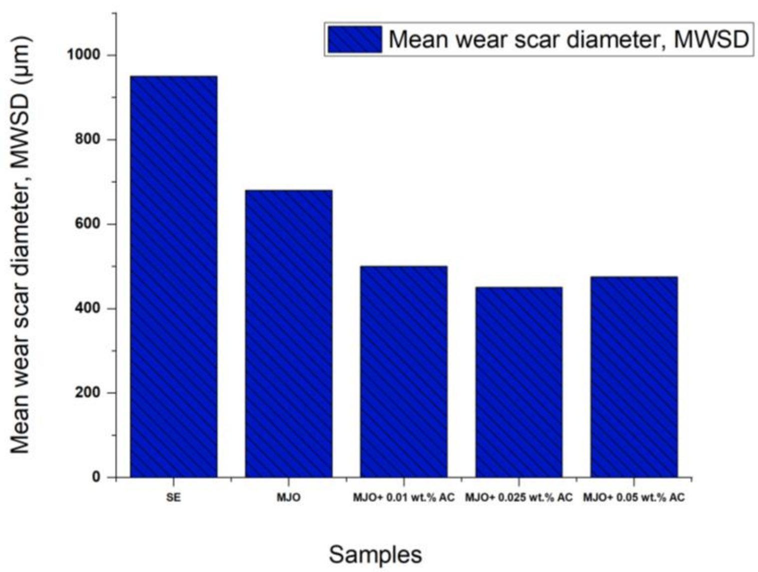


Figure 2: Graph of mean wear scar diameter (MWSD) for all samples.

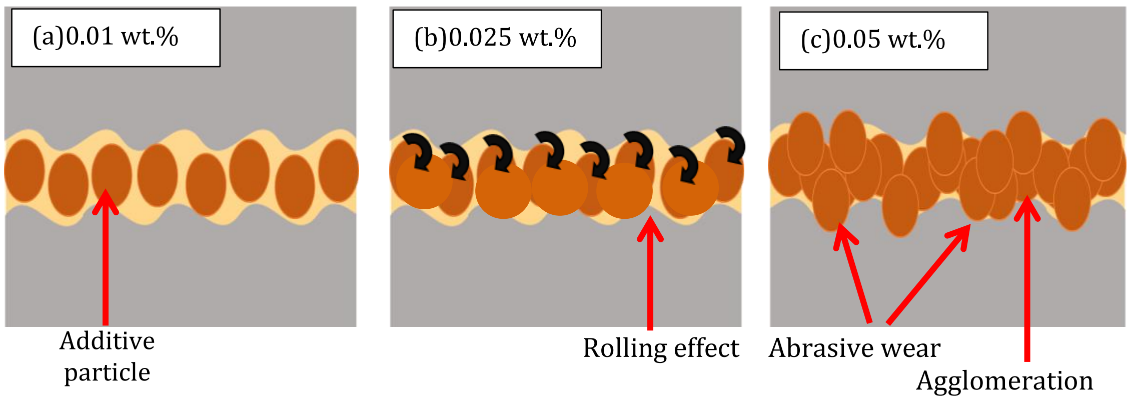


Figure 3: Schematic diagram of lubrication film in MJO with various concentrations of AC.

3.1 Tool Life and Tool Wear

The development of average flank wear (VB_B) and notch wear (VB_N) for MJO + 0.025wt.% AC and SE were shown in Figures 4 and 5. From the results, the tool lubricates by SE failed when notch wear (VB_N) exceeded 0.6mm at 6000mm cutting length and 42 minutes machining time. However, the tool was lubricated by MJO + 0.025wt.% AC, failed when its average flank wear (VB_B) exceeded the tool wear criterion of 0.3mm at 7000mm cutting length and 49 minutes machining time. The nanofluid (MJO+0.025 wt. % AC) delivers a 17 % increase in tool life as compared to SE. In Figure 4 and Figure 5, it can be seen that the average flank wear (VB_B) and notch wear (VB_N) of MJO+0.025 wt. % AC were lower than SE. This is because of MJO, the developed TMP triester had long and branched molecular chains possessed good low-temperature characteristics. The adsorption potential on the metal surface increased as the connections between ester chains in MJO molecules became stronger. The polar structure of MJO samples decreased the tool wear by generating a protective layer at the contact surfaces that reduced wear and friction (Talib et al., 2017). The addition of 0.025 wt.% of AC greatly improves the tool life of the cutting tool. This was because of the porous structure of activated carbon and its good adsorption capabilities (Oginni et al., 2019). Consequently, it serves as a spacer between metal surfaces, preventing them from colliding (Radhiyah & Jun Li, 2020).

Figure 6 shows the SEM image of the cutting tool at the flank face for MJO + 0.025wt.% AC. From the SEM image, there was adhesion wear caused by the sliding effect of the chips at the tool surface during the deformation process generate high temperature (Talib & Rahim, 2018). The material of the tool was peeled off by hard particles that can be loose, resulting in abrasion wear at the flanks. The tool's broken hard particles and sliding chips caused the abrasion grooves to form. Furthermore, severe abrasion at the depth of the cut line on the flank face causes notch wear on the flank face (Chetan et al., 2016; De Melo et al., 2006). The appearance of notch wear was not very significant as there was the adhesion of the chips and activated carbon at the flank face. Figure 6 shows the deposition of activated carbon nanoparticles at the flank face at 56.55 wt.%. The elements of C, O, Fe, Mn, P, and S that originated from workpiece material and a thin layer of nanofluid had been deposited at the contact surface were demonstrated and proved by an energy dispersive X-ray spectrometer (EDS) spectrum in adhered material as shown in Figure 7.

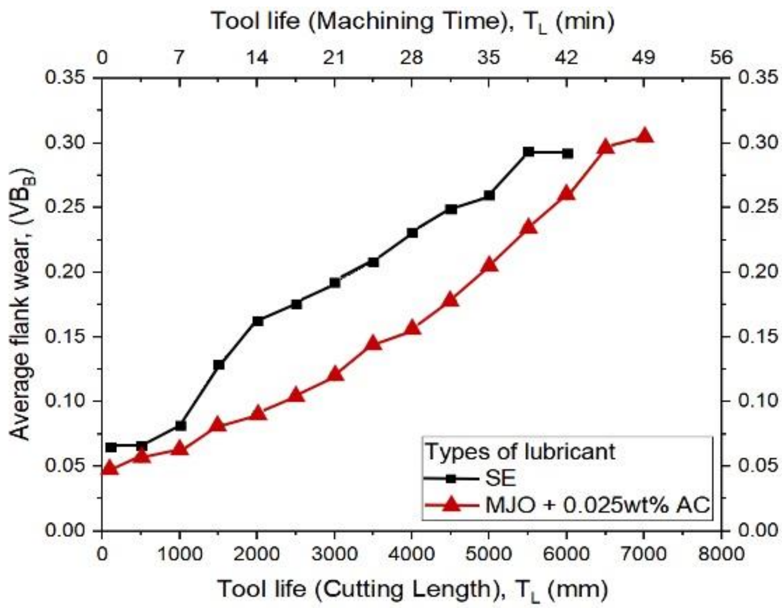


Figure 4: Graph of average flank wear (V_{BB}) of SE and MJO + 0.025wt.% AC.

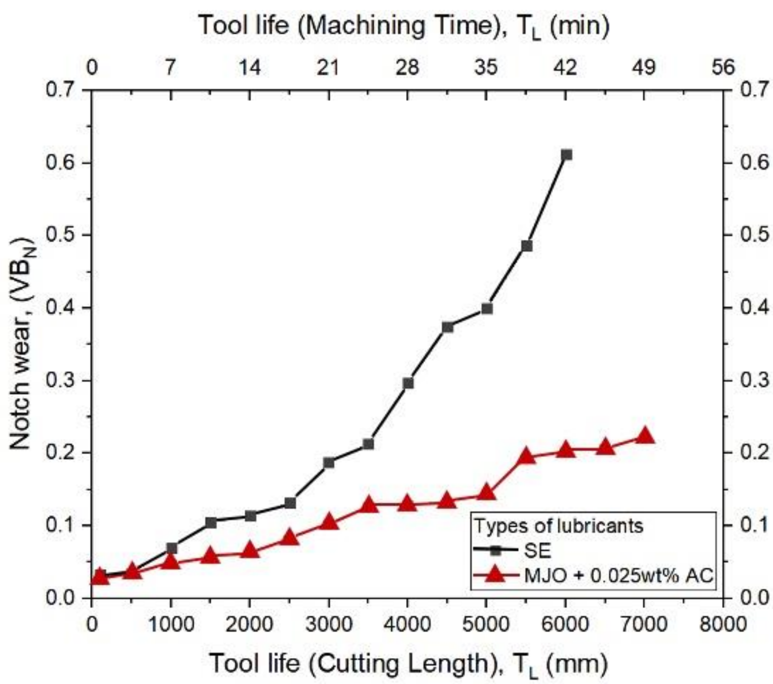


Figure 5: Graph of notch wear (V_{BN}) of SE and MJO + 0.025wt.% AC.

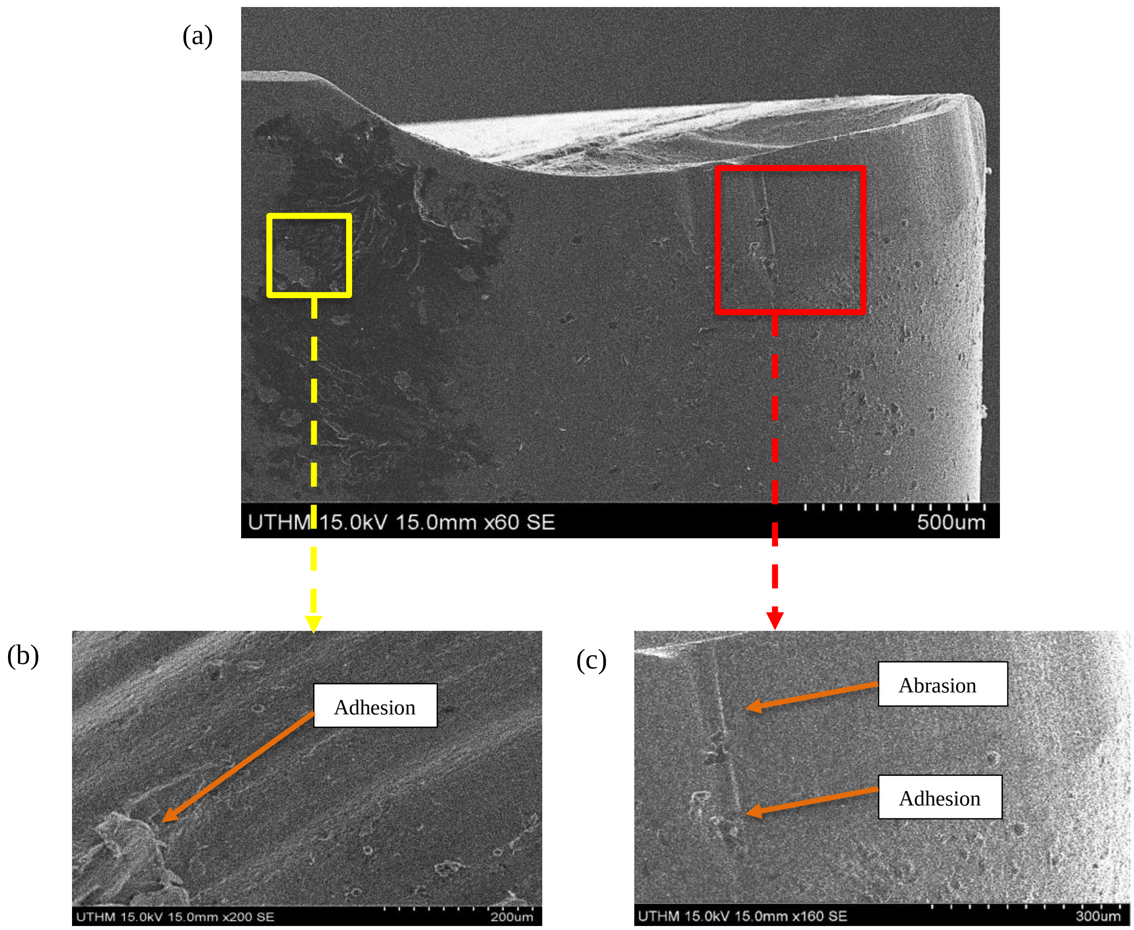
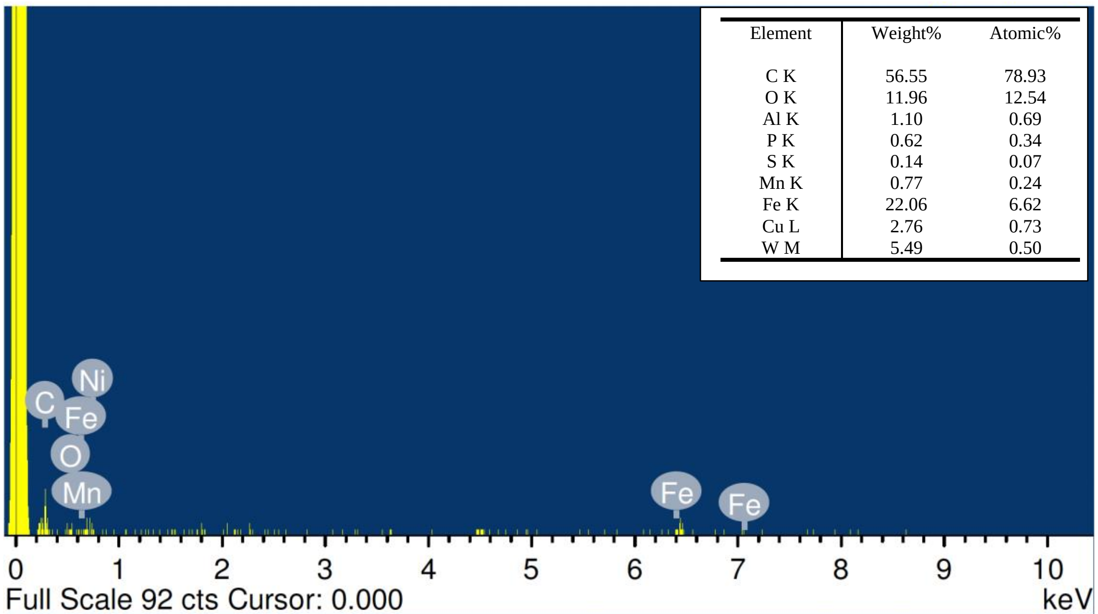


Figure 6: SEM images at flank face for MJO + 0.025wt.% AC (a) flank wear at a magnification of 60 (b) image of adhesive wear at a magnification of 200 (c) image of abrasive wear at a magnification of 160.



Element	Weight%	Atomic%
C K	56.55	78.93
O K	11.96	12.54
Al K	1.10	0.69
P K	0.62	0.34
S K	0.14	0.07
Mn K	0.77	0.24
Fe K	22.06	6.62
Cu L	2.76	0.73
W M	5.49	0.50

Figure 7: EDX spectrum at flank face for MJO + 0.025wt.% AC.

CONCLUSION

In a conclusion, modified jatropha oil (MJO), MJO+0.01wt.% Activated carbon (AC), MJO+0.025wt.% Activated carbon (AC), and MJO+ 0.05wt.% Activated carbon (AC), shows better results in coefficient of friction (COF), mean wear scar diameter (MWSD), and tool life compared to synthetic ester (SE). The addition of AC nanoparticles to MJO results in improved lubricant and tribological properties. In addition, the results showed that MJO + 0.025wt.% Activated carbon (AC) has lower coefficient of friction (COF), smaller mean wear scar diameter (MWSD) and longer tool life in terms of machining time and cutting length, making it an excellent candidate for use as an environmentally friendly MWF in the machining process.

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