Machining studies on Monel K – 500 using TiAlN coated tungsten carbide inserts under Ag nanoparticles incorporated modified pongamia pinnata oil lubrication

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Abstract

Research investigations conducted in the past has shown that conventional petroleum based lubricants can be replaced with vegetable lubricants. Vegetable oil lubricants do not pollute the environment, as they are biodegradable. In this investigation, pongamia pinnata oil was used as lubricant, to during turning experiments. The physico chemical properties of modified pongamia pinnata oil were evaluated. Ag Nanoparticles were incorporated into the modified pongamia pinnata oil and it was subjected to tribological investigations. In this investigation, the effect of Ag nanoparticles in improving the lubricating aspects of the modified pongamia pinnata oil was studied. The aim of this investigation is to identify the effect of the nanoparticle incorporated bio-lubricant coolant on Monel K 500. In this study, using TiAlN coated triangular tungsten carbide inserts, Monel K 500 was subjected to turning under three conditions such as dry, minimum quantity lubrication and Ag nanoparticles incorporated vegetable oil lubrication. It was observed that the properties of the bio lubricant affected the turning output responses to such as cutting force, machining temperature, tool wear and surface roughness of the workpiece (Monel K 500). Machined surface was evaluated using scanning electron microscope, electron back scatter diffraction analysis and x-ray diffraction analysis. Turning operation conducted with 2% Ag nanoparticles incorporated modified pongamia pinnata oil lubrication was better than turning conducted under dry and lubricated conditions. Industrial wastes and toxic effluents can be minimised by switching over to bio lubricants and coolants.

1. Introduction

During any machining process, friction is generated between the work-piece and tool. This friction induces frictional heat and drastically increases the machining temperature [1]. The mechanical properties of the interacting surfaces may change due to the frictional heat and the cutting tool may get damaged [2]. Due to this issue, machining becomes ineffective. Different techniques are being used for minimizing the heat generated in the machining region. By using water/oil based coolants [3], cryogenic coolant [4] and minimum quantity lubrication [5] techniques, heat reduction in the machining region are done. Metal Working Fluids (MWFs) and lubricants help in reducing the heat generated in the machining zone and also minimize the friction between the work-piece surface and cutting tool [6]. Even though water soluble cutting fluids are widely used as MWFs, there are certain drawbacks associated with them [7]. Conventional MWFs cannot be treated and it pollutes the environment. Hence, the need for bio lubricants has increased.

Minimum Quantity Lubrication (MQL) technique plays an important role in reducing the heat in the cutting zone, with a minimum quantity of lubricant/MWFs sprayed in the machining region. Even though petroleum based lubricants/coolants are being used on a large scale, they are not sustainable and cause heavy pollution to the environment. In the recent years, petroleum based products are being consumed at very high...
rates and they are getting depleted. These issues have led researchers to investigate and develop sustainable and biodegradable lubricants/coolants for industrial use. Sustainable development suggests replacement of conventional petroleum based lubricants by vegetable oil based bio lubricants [8]. Compared to petroleum based lubricants, the efficiency of vegetable oil based bio lubricants as MWFs were found to be better. Further, incorporation of nanoparticles in vegetable based oils significantly improved the properties associated with lubrication [9]. The efficiency of nanoparticles infused with vegetable oils as lubricant was found to be considerably higher than normal MWFs [10].

Biodegradable and pollution free nature of vegetable oil lubricants has led manufacturers to replace conventional petroleum oils by vegetable based oils. Vegetable based MWFs are ready to manufacture as they are derived from highly sustainable sources. Presence of polar esters, unsaturated fatty acids (having continuous and long chains) help vegetable based oils to perform as excellent MWFs [11]. In previous investigations, even though the coefficient of friction was brought down by using vegetable oil lubrication during machining, the wear rate was substantially high [12]. During tribological tests under vegetable oil lubrication, the metal oil layer was wiped away during sliding [13]. It resulted in formation of a non-reactive rough layer, increasing wear in-between the sliding layer [14]. The fatty acids present in vegetable oil lubricants induce a biochemical action in the interacting surfaces [15]. Even though vegetable oil lubricants reduce friction coefficient, wear rate was found to be higher. Use of as prepared vegetable based oils did not contribute much to wear reduction. Proper formation of vegetable lubricants is needed for improving its lubrication properties. Even though processed vegetable oils exhibited physico chemical characteristics similar to mineral oils [16], the performance of such processed vegetable oils were lower. This was attributed to the peculiar behaviour of vegetable based oils, compared with mineral oils. Ease of oxidation [17], resistance created by elastomers [18] and unstable temperature [19] were attributed to be the limitations of vegetable oils. Presence of triglycerides in vegetable based oils [20] helps to retain its lubricating properties at high temperatures up to 60°C. Some vegetable oils work at temperatures as high as 105°C [21]. Vegetable oils used for preparing MWFs should meet ISO 14000 requirements [22], for ensuring better quality. Vegetable oil derived from Neem [23], Jojoba [24], Jatropha [25], Almond [12] can be used for preparing MWFs. There is a lot of scope for conducting research to identify different proposing methods for vegetable oils. In tribological studies, vegetable oils can be used for lubrication. Pongamia pinnata grows in different terrains and can survive in a volatile environment. The Pongamia pinnata plant is found extensively in India, Bangladesh, Vietnam, China and Malaysia. As pongamia pinnata can withstand volatile agro climatic conditions, it is grown in different parts of India. Pongamia pinnata seeds are used to prepare oil and it can be easily and safely stored for a long time [26]. Pongamia pinnata has medicinal benefits and it is used to prepare anti allergic creams in pharmaceutical industries [27]. A lot of research is being put in by researchers all over the world to use pongamia pinnata oil as additive/substitute in fuel, coolant and lubricant. Even though pongamia pinnata oil is grown in India, the potential of its oil has not been exploited to the fullest extent. Pongamia Pinnata oil has a lot of scope to be used as MWF in different machining operations [28]. Latest researchers have assessed the efficiency of pongamia pinnata oil as a lubricant. Experimental results indicate that pongamia pinnata oil can be used as a lubricant and coolant in machining studies. For enhancing the lubricating aspects of vegetable oils, the oxidation rate has to be minimized [8]. The available oil processing mechanisms do not offer a viable solution to convert pongamia pinnata oil into MWFs.

Presence of vegetable oil based lubricant in the machining zone causes improvement in productivity and surface texture, while reducing the tool wear. Previous investigations reported significant reduction in friction and heat in the machining zone, on incorporating MQL [29] and cryogenic lubrication of [30]. Researchers tried to strike a balance between ease of operation and economic viability. Tool life and cutting speed increased upon incorporating MQL. Long term sustainability suggests that environmental factors and parameters should be incorporated during machining [31]. The effectiveness of biodegradable vegetable oils was identified by conducting tribological investigations using them. Increase in tool life was observed upon combining high friction coefficient particles with low viscosity oils [32]. For improving the performance of lubricants, additives are used [33]. During tribological interactions, presence of additives in vegetable oils aids in formation of triacylglycerol [34]. Presence of additive incorporated vegetable oil in the machining zone reduces tool wear, cutting force and machining temperature [35]. The characteristics of lubricant depend upon its parent vegetable oil and additive [36]. The quantity and property of the additives incorporated in vegetable oils should be thoroughly examined. The additives that are mixed in the vegetable lubricant should be properly dissolved or dispersed evenly throughout the carrier oil.

During tribological interactions, presence of solid additives in lubricants enhances the consistency and workability of the lubricants [37]. Ag nanoparticles are one such additive, which is non-reactive and can act as friction reducers [38]. Ag nanoparticles are spherical in shape and have smooth edges (approximately 25 nm – 35 nm in diameter). Many research investigations have been reported in using nanoparticles to reduce triboreduction, but they were concentrated on petroleum based lubricants [39, 40]. In recent times, research is being conducted to imbibe nanoparticles in edible and biodegradable oils. Researchers have concluded that edible oils
can be used as lubricants [41]. Tribological studies using pongamia pinnata oil as biolubricant indicated that pongamia pinnata oil reduced wear rate [42]. Ag nanoparticles incorporated lubricant caused reduction in frictional wear and heat generated in the machining region [43]. By increasing the effectiveness of molecular deposition films [44], Ag nanoparticles aid in reducing friction and wear during tribological interactions [45].

Tool inserts are efficient and provide cost effective solution in material removal, when they are used in machining metals and metal alloys [46]. Tungsten carbide inserts are preferred in machining as they withstand higher erosion wear withstand higher erosion wear during hard material machining [47]. Continuous and forced frictional contact causes tool wear [48]. When the machining temperature increases beyond 650 °C, undesirable modifications in microstructure & reduction in surface quality in nickel based alloys [49]. Strain hardening and micro-hardness variations occur in nickel based alloys at higher machining temperatures [50]. At higher frictional operations, surface integrity characteristics of nickel based alloys deteriorate [51]. Coatings help in reducing frictional wear of tool [52]. Titanium based coatings isolates the base material from excessive wear and tear [53]. Nitride based coatings offer higher surface protection against erosive and frictional wear [54].

2. Materials and methods

2.1. Synthesis of pongamia pinnata oil

For this investigation, high quality pongamia pinnata oil was used. It was subjected to chemical processing for reducing the quantity of free fatty acids in pongamia pinnata oil [55]. Pongamia pinnata oil was subjected to epoxidation treatment by using trimethyl propane. For chemical treatment of pongamia pinnata oil, peracetic acid was indigenously prepared. Peracetic acid was made by combining acetic acid, hydrogen peroxide and sulphuric acid [56]. 74.24 ml of peracetic acid was mixed with 21.44 ml of pongamia pinnata oil and the solution was maintained at 20 °C for 6 h. After 6 h, the processed oil was poured in water and allowed to settle for 1 h. Epoxy oil was allowed to float collect in the top. Meanwhile water was collected in the bottom. From the bottom, water was removed. Ag nanoparticles were added in the modified pongamia pinnata lubricant to improve its lubrication properties. Ag nanoparticles help in improving the load wear index [57] of the lubricant fluids. Presence of Ag nanoparticles help in reducing the wear scar diameter [58], during tribological investigations and it improves anti-wear properties of metal cutting fluids [59]. During tribological interactions, Ag nanoparticles form a thin tribofilm layer on the wear surfaces [60] (both cutting tool and workpiece). This tribofilm mechanism was found to be responsible for improving the tribological characteristics of the nanoparticles incorporated metal working fluids [61]. The Ag nanoparticles present in the metal working fluids tend to fill the wear cracks [62]. This prevents the crack from propagating. It reduces the actual metal to metal contact and friction. It forms a triphosphilic film to improve the load wear index and anti-wear ability of the metal working fluids. The tribofilm formed over the wear surfaces, on using Ag nanoparticle incorporated lubricants were primarily found to be due to mechanical mixing, rather than chemical interactions [63]. This is due to the inert and non reactive nature of Ag nanoparticles. This makes Ag nanoparticles to be a favorable additive for lubricants, compared to other reactive additives [64].

99.9% pure Ag nanoparticles were used as additives in the research. The sizes of procured Ag nanoparticles ranged from 20 nm to 35 nm. Ag nanoparticles were added to epoxidized pongamia pinnata oil. Sodium lauryl sulfate was used for agitating the mixture [65]. Surfactants were added to the nanoparticle incorporated lubricants at 2% by weight. For ensuring better lubrication properties for 2% Ag nanoparticles incorporated modified pongamia pinnata oil, attachment of the surfactant to Ag nanoparticles has to be ensured. For dispersion of Ag nanoparticles in modified pongamia pinnata oil, binding between the surfactants and the nanoparticles are very important. For ensuring better dispersion stability of Ag nanoparticles in modified vegetable oil lubricant, 2% surfactant was used [66].

The geometry and structure of Ag nanoparticles were assessed by using Transmission Electron Microscope (TEM). JOEL—2100 high resolution transmission electron microscope was used for TEM imaging. Using Ultraviolet–visible spectrophotometer (Make—Genesyss) and Fourier Transform Infrared Spectrometer (Make—Fisher), Ultraviolet–visible spectroscopy and Fourier Transform Infrared Spectroscopic evaluation of Ag nanoparticles were done. Using Rigaku make x-ray Diffraction (X-RD) equipment, with Cu target, 40 KV voltage, 30 mA scintillating current, with step size of 0.002, from 20 ° to 80° two theta X Ray Diffraction (X-RD) studies were conducted. TEM image of Ag nanoparticles is shown in figure 1. The properties of Ag nanoparticles were characterized using UV–vis spectroscopy and Fourier Transform Infrared Ray (FTIR) spectroscopy (Make—Trivitron). Figure 1(a) shows the TEM image of Ag nanoparticles. Ag nanoparticles of size between 25–35 nm were observed. The nanoparticles were found to be round and with abrupt boundaries. Figure 1(b) shows selected area diffraction (SAED) pattern of Ag nanoparticles Bright patches were identified in alternate onion ring shapes. The rings indicated the presence of Ag assigned to [67, 200, 220] and [311]. Figure 1(c) shows the particle size distribution of Ag nanoparticles. Maximum number of Ag nanoparticles was observed with 25–28 nm in size.
Figure 2(a) shows UV–vis spectrum of Ag nanoparticles [68]. Absorbance peak at 410 nm was observed confirming Ag nanoparticles. Figure 2(b) shows FTIR graph of Ag nanoparticles. Transmittance was observed at 3431 cm⁻¹, 2924 cm⁻¹ and 1622 cm⁻¹ [69]. Figure 2(c) shows X–RD spectrum of Ag nanoparticles. Peaks were observed at 38.09°, 45.87° and 65.01° indicating face centered cubic structure of Ag nanoparticles at planes (111), (200) and (220) [70].

For suspending the Ag nanoparticles in the vegetable oil lubricant, it was stirred using a magnetic stirrer for 4 h at 600 rpm. Then it was agitated using ultrasonicator for half an hour. For identifying the crystalline structure of Ag nanoparticles, it was subjected to x-ray diffraction analysis. Three lubrication conditions were used in the experiments, such as with untreated oil, modified vegetable oil and Ag nanoparticles incorporated modified oil.

In this study Ag nanoparticles were added to lubricants at 2% by weight. Ag nanoparticles in the lubricant were expected to artificially smooth the shearing surfaces [71], during tribological interactions. As Ag nanoparticles exhibit low shear strength [72], under elevated temperature and pressure, it forms an adsorption film [73] over the wear surfaces. Formation of tribofilm affects the anti wear properties. 2% by wt addition of Ag nanoparticles in metal working fluids helps to fill the cracks and micropits of the shearing surfaces [74]. At this concentration, Ag nanoparticles act as spacers and exhibit good interfacial compatibility between cutting tool and workpiece [75]. They exhibit reasonably good friction and wear resistant properties. This improvement in lubricating aspects is attributed to the synergistic self-lubricating effect of Ag nanoparticles at 2% by wt concentration [76]. Untreated pongamia pinnata oil was designated as PPO, modified pongamia pinnata oil was designated as MPPO and 2% Ag nanoparticle incorporated modified pongamia pinnata oil was designated as MPPO + 2% Ag.

2.2. Properties of lubrication oil
The properties of PPO, MPPO and MPPO + 2% Ag were evaluated and tested by using ASTM standards. As per ASTM D—445 standards, the viscosity of the vegetable oil combinations were studied [77]. At 40 °C and 100 °C kinematic viscosity measurement experiments were conducted. For reducing the experimental errors, each condition was tested three times and the average of the three was recorded. As per ASTM—D 92 standards, the flash point of three lubrication combinations were studied [78]. Density of the vegetable oil combinations were studied using pycnometer as per ASTM—2270 standards [79]. As per ASTM D 6304 standards, the H₂O content in the lubricants was studied [80]. Karl Fischer Titrator was used for studying the water content in the samples.
Using UV–vis spectroscopy and FTIR spectroscopy studies, the lubricant oil and its combinations were evaluated. The equipments and experimental setup used for identifying the physico chemical characteristics of the vegetable oil and modified vegetable oil is shown in figure 3.

Figure 3(a) shows the density measurement setup with the three vegetable oil combinations, Pycnometer and digital weighing scale. Figure 3(b) shows Karl fischer Titrator for measuring the water content in the vegetable oil combinations. Figure 3(c) shows the flash point testing equipment and figure 3(d) shows the viscosity measurement equipment.

2.3. Machining studies
Using a heavy type computer numerically controlled turning centre, the turning experiments on Monel 500 rods were conducted. Triangular tungsten carbide tool inserts (Designation—HM390 TDKT 1505PDR) were used for turning experiments. Schematic representation of the WC insert is shown in figure 4. Its dimensions were $D = 16.2 \text{ mm}, a_p = 12.7 \text{ mm}, r = 1.2 \text{ mm}, F = 1 \text{ mm}, d_i = 11.4 \text{ mm}, T = 5.85 \text{ mm}$.

High velocity oxy fuel thermal spray technique [81] was used to coat TiAlN over the triangular insert. For coating the tool inserts TiAlN material was used. 99.9% pure TiAlN (micro sized) powder was used. As the coating powder was highly pure, it was used in the experimentation process without further processing. The important physical and chemical properties of TiAlN were recorded from the manufacturer’s catalogue. The as-received TiAlN powder was subjected to XRD and SEM analysis to identify its composition and geometrical properties.

Indigenously prepared HVOF equipment (Spraying setup Make- Praxair & Stellite) was used was used for spraying over the tool inert. The HVOF spraying setup is shown in figure 5.

HVOF thermal spray coating technique has been widely used in many research investigations and industrial use [82–84]. Liquefied Petroleum Gas (LPG) was used as fuel and Oxygen was used as the combustion agent. Using fixtures, the tool inserts were held during the HVOF spraying process. From previous literatures and trial
Figure 3. Photos of equipments used of evaluating the physico chemical characteristics (a) Density measurement, (b) Water content measurement (Karl fischer Titrator), (c) flash point measurement apparatus, (d) viscosity measurement apparatus.

Figure 4. Schematic representation of triangular WC inserts.
experiments, the HVOF process parameters values were fixed. At oxygen flow rate of 245 lpm, fuel flow rate of 55 lpm, distance between spraying nozzle and tool insert surface of 175 mm, TiAlN feed rate at 30 g min$^{-1}$ fuel pressure at 0.4 MPa, oxygen pressure at 0.5 MPa and air pressure at 0.35 MPa [85], HVOF thermal spraying was done. A coating thickness of 0.75 to 0.8 μm was obtained after a single coat. TiAlN powder was heated to very high temperature and accelerated as high velocity gas jet towards the workpiece. As high temperature nano droplets [86], they hit the workpiece. On the workpiece, these droplets flatten to form lamellae of splats. These splats pile up to form a continuous and highly dense coating [87]. After completion of a single coat, the coated inserts were cooled and the thickness of the coatings was measured. The thickness of the coatings was measured at three different regions, and the average of the three was evaluated. Prior to measuring the coating on the substrate, the coatmeter was calibrated with standard films. Probe of the coatmeter was cleaned and with standard thickness film of 0.5 μm, the accuracy and precision of the coatmeter was evaluated. This procedure was used to eliminate errors during coating thickness measurement. According to trials conducted in previous investigations [88–90], the thickness of the coating on inserts was fixed as 2.50 μm. A micro-coat meter (Fischer coating tester) was used for measuring the coating thickness. It was calibrated with standard micro films before measurements. Photograph of TiAlN coated tungsten carbide inserts are shown in figure 6.

After coating the WC tool insert, its surface was subjected to XRD, SEM and Electron Back Scattering Diffraction (EBSD) studies. EBSD studies were conducted to identify the surface modifications in the coated tool inserts.

The machining parameters were fixed as per previous literatures and trial experiments. The tool was fitted with a chip breaker. At 12° negative rake angle and 0° as clearance angle, the tool was made to turn at cutting speed of 250 m min$^{-1}$. The feed rate was maintained at 0.25 mm/rev and the cutting depth was fixed at 1.2 mm [81].
Minimum Quantity Lubrication (MQL) setup was used for conducting turning experiments under lubricated conditions. The MQL setup used in the experiments has been shown in figure 7(a) and the MQL test kit assembly is shown in figure 7(b).

For MQL spray setup, 2.25 mm diameter spray nozzle was used. The flow rate was maintained at 0.15 l h$^{-1}$, the input pressure was set constant at 0.5 MPa [91]. The process parameters for the Minimum Quantity Lubrication setup were selecting after considering the values indicated in the previous literatures and trial experiments. Out of the three parameters, two were retained as constant and one parameter was increased, and experiments were conducted. The chip forming nomenclature and surface finish of the machined samples were evaluated. Accordingly, the process parameters of MQL setup were fixed.

Monel K 500 rods of 60 mm diameter and 120 mm length were used as workpiece. Monel K 500 is used in pump shafts, impeller, propeller shafts, valve components for ship engines [92], offshore drilling equipments and drill collars for oil well boring equipments [93]. It is used for fabricating centrifugal pump components to be used in high salt content water [94].

Turning center fitted with MQL setup was used for performing the experiments. The nozzle of the MQL was placed 6 mm away from the cutting edge, nearer to the flank and rake face for ensuring adequate lubrication. Throughout the entire duration of the experimentation process, the tool and work-piece was sprayed with vegetable oil lubricant. The edge of the triangular tungsten carbide tool insert was used for turning. A dynamometer was fixed to the cutting tool for recording the cutting forces. Using a non-contact type infra red temperature transducer, the fluctuations in cutting temperature was recorded. The temperature sensor was made to move in longitudinal axis, along with the tool post so as to measure the temperature throughout the turning process. For all turning experiments, the reflective ambient temperature was fixed at 26 °C and emissivity as 1. The surface roughness of Monel K 500 workpieces were measured before and after conducting the turning experiments. TA Instrument surface roughness testing equipment was used in the experiments. Using tool maker’s microscope the wear in the flank surface of the tool was identified. The tool maker’s microscope used in the experiments has been shown in figure 8.

Tool wear was evaluated according to ISO 3685 standards. Using Leads India make—Scanning Electron Microscope, microstructural evaluation were done. The wear pattern in the used cutting tool was studied.

For all turning experiments, TiAlN coated tungsten carbide inserts were used. TiAlN coated tungsten carbide inserts were used as the coated reference inserts (CRI) for conducting dry experiments without lubrication. Machining studies were conducted using TiAlN coated tungsten carbide inserts with pongamia pinnata oil (PPO) lubrication, modified pongamia pinnata oil lubrication (MPPO) and modified pongamia pinnata oil with 2% Ag nanoparticles (MPPO + 2% Ag) lubrication under MQL. The machined samples under different lubrication conditions are shown in figure 9.

Mean flank wear (MFW) $\geq$ 0.3 mm, Maximum flank wear (Max FW) $> 0.5$mm and maximum notch wear (Max NW) $> 0.5$mm were the wear criteria considered for the experiments. Carl Zeiss make Electron Backscatter Diffraction (EBSD) equipment was used to conduct EBSD studies on the workpiece, before and after conducting machining studies. The grain orientation and grain sizes were identified. The scanning area was 600 $\times$ 400 $\mu m^2$ and the step size was 1 $\mu m$ and EBSD evaluation was done using TSL OIM software.
3. Results & discussion

3.1. Physico-chemical characteristics of pongamia pinnata lubricant oil

The important physico-chemical characteristics such as kinematic viscosity (KV), viscosity index (VI), density (D) and water content of the vegetable oil lubricant were evaluated. The properties of the lubricant PPO, MPPO & MPPO + 2% Ag are shown in table 1.

Addition of Ag nanoparticles in solid state caused a reduction in water content. Increase in flash point was observed for MPPO + 2% Ag nanoparticles combination, compared to PPO. Chemically modified pongamia pinnata oil exhibited increase in kinematic viscosity, compared to PPO, which further increased on adding Ag

Figure 8. Tool makers microscope used to study the tool wear.

Figure 9. Machined samples under different lubrication conditions.
nanoparticles. The variations in kinematic viscosity of the lubricants upon increasing the temperature are shown in figure 10. Reduction in viscosity was observed on increasing temperature. Thermal fluctuations in cutting zone cause a reduction in lifetime of the lubricants. High temperature generated in the tribological surfaces causes creation of carbon based surfaces. This reduces the efficiency of lubrication. Breakage of covalent bonds in lubricant oil occurs at high temperature causing free radical reaction, thereby reducing viscosity [95]. Kinematic viscosity increased on adding Ag nanoparticles to MPPO, compared to base oil. Increase in length of carbon chain causes kinematic viscosity of the oil to increase. At 100 °C, kinematic viscosity of PPO oil was least. MPPO and MPPO + 2% Ag nanoparticles exhibited better kinematic viscosity at 100 °C. Viscosity Index (VI) is an indication of the operating temperature, which the modified vegetable oil can withstand, during usage. High values of VI indicate that fluctuations in temperature do not affect the viscosity. Vegetable oils with high VI offer sustainable lubrication at a huge temperature range [96]. During high temperature tribological interactions using vegetable oil lubrication, the lubrication film becomes thin. Thickness of the lubricating film increases on reducing the operation temperature [97]. VI of PPO increased up on subjecting it to chemical modification. VI further increased on adding Ag nanoparticles. This increase in VI was due to the chemically inert nature and thermal stability of Ag nanoparticles [98].

UV–vis graphs of the lubricant combinations are shown in figures 11(a)–(c). FTIR graphs of the lubricant combinations are shown in figures 11(d)–(f).

UV–vis graph of PPO (figure 11(a)) shows absorbance peak at 406.52 nm, UV–vis graph of MPPO (figure 11(b)) shows absorbance peak at 422.57 nm, UV–vis graph of MPPO + 2% Ag nanoparticles (figure 11(c)) shows absorbance peak at 338.29 nm indicating Ag nanoparticles and absorbance peak at 468.06 nm indicating modified pongamia pinnata oil [99, 100].

FTIR spectrum of PPO (figure 11(d)) shows transmittance peaks at 3582.85 cm⁻¹ indicating (N-H) free pyrroly, 3011.28 cm⁻¹, 2399.04 cm⁻¹ indicating amino acids with N-H stretch, 2068.14 cm⁻¹ indicating C-N strengthening, 1757.10 cm⁻¹, 1874.16 cm⁻¹ and 723.66 cm⁻¹. FTIR spectrum of MPPO (figure 11(e)) shows transmittance peaks at 3462.79 cm⁻¹ indicating (N-H) free pyrroly, 3242.05 cm⁻¹, 3201.92 cm⁻¹, 2750.41 cm⁻¹, 2098.24 cm⁻¹, 1957.77 cm⁻¹ indicating C-C stretching, 1827.34 cm⁻¹, 1696.90 cm⁻¹, 1586.53 cm⁻¹, 1395.90 cm⁻¹, 1054.76 cm⁻¹. FTIR spectrum of MPPO + 2% Ag (figure 11(f)) shows transmittance peaks at

![Figure 10. Variations in kinematic viscosity of the lubricant on increasing temperature.](image-url)

| Composition of lubricant | Density at 15 °C (kg m⁻³) | Kinematic viscosity (KV) at 40 °C (mm² s⁻¹) | Kinematic viscosity (KV) at 100 °C (mm² s⁻¹) | Viscosity index (VI) | Water content (WC) % | Flash Point (°C) (FP) |
|-------------------------|--------------------------|-------------------------------------------|-------------------------------------------|---------------------|--------------------|----------------------|
| PPO                     | 892                      | 43.17                                     | 7.81                                      | 167                 | 0.037              | 177                  |
| MPPO                    | 851                      | 124.18                                    | 10.84                                     | 207                 | 0.044              | 219                  |
| MPPO + 2% Ag            | 837                      | 128.62                                    | 11.63                                     | 198                 | 0.033              | 228                  |
3402.59 cm⁻¹ indicating (N-H) free pyrrols, 1857.44 cm⁻¹, 1646.79 cm⁻¹, 1375.83 cm⁻¹, 1014.63 cm⁻¹ [100, 101].

3.2. Cutting force variations
Turning experiments were conducted on Monel K 500 using TiAlN coated tungsten carbide inserts under vegetable oil lubrication and the variations in cutting force, temperature and surface roughness were studied. During machining, reduction in workpiece material occurred. The separated chips from the workpiece slides through rake surface of the cutting tool and causes an increase in frictional heat. This generated frictional heat affects the cutting force [102]. Hence, during the entire machining process, lubrication of cutting tool—workpiece interface is important. Figure 12 shows the variations in cutting forces with different types of lubricant combinations.

At standard conditions, the cutting forces were evaluated. Cutting force generated during turning using TiAlN coated insert without lubrication was very high (486N). This was considerably greater than the cutting forces generated while machining under PPO, MPPO and MPPO + 2% Ag lubrication. The mean cutting force generated during machining under PPO, MPPO & MPPO + 2% Ag lubrication conditions were 5.14%, 7.61% and 12.96% lesser than the cutting forces generated under dry conditions. Synthetic vegetable oil lubricants exhibit adsorption of film on the workpiece surface and tool. In sliding surfaces, interaction of additives in vegetable oil molecules helps in formation of protective layers. Presence of protective layers over metal substrates enhances surface lubrication. This ensures smoother distribution of shear stresses which are formed during tribological interactions [67]. Quick and smooth distribution of the stresses developed in tool and workpiece interface causes friction reduction [103]. In vegetable oils, the polar fatty acid structure is long and branched [104]. Interaction of such oil molecules with metal surfaces results in formation of high strength lubricant films [105]. These types of films are formed due to adsorption mechanism, which reduces the contact length and cutting forces [106]. Presence of Ag nanoparticles in the lubricant reduces stick-slip issues [67] in cutting edges of tool. This is due to adsorption of Ag nanoparticles incorporated vegetable lubricant over the metal surfaces [107]. On increasing the additive quantity in cutting fluids, increase in adsorption activity of the metal cutting fluid molecules over the sliding surfaces were observed [108]. Presence of vegetable oil layer in wear surfaces causes reduction in interfacial shear stress and asperity contact [109]. Reduction in interfacial shear stress occurs due to better adsorption of vegetable oil molecules over metal surface. The protective film is formed by physical adsorption between the interacting surfaces. Films formed using physical adsorption were found to be durable than protective films formed by chemical reactions [110]. Adsorbed film reduces metal to
metal contact by resisting penetration of metal asperities [111] during machining operations. The adsorption film formation process over metal surfaces gets affected by the viscosity of the vegetable oil used. By using viscosity modifiers, vegetable oils were found to exhibit better lubrication properties at higher temperatures [112].

Lubricating film in between the interacting surfaces reduced the cutting forces. Concentration of the lubricant and the polarity of the additive incorporated lubricant determine the adsorption mechanism of the lubricants during tribological interactions [113]. Additives in lubricant roll during tribological interactions and reduced friction. Hence, cutting forces was found to decrease on adding Ag nanoparticles. Deposition of Ag nanoparticles incorporated MPPO in the machining region was done in a steady manner, for reducing the sliding friction throughout the machining process. Rolling of Ag nanoparticles during machining causes reduction in cutting forces [114], which in turn reduces the energy involved in machining operation. The vegetable oil lubricants used in this investigation reduced the machining energy and also helped in protecting the environment by reducing pollution.

3.3. Machining temperature
During turning operation, heat is generated during shear and plastic deformation. Another reason for heat generation is due to slip that occurs between tool and chip interface. Friction developed between the tool and workpiece also induce heat generation [115]. For reducing the damage to the cutting tool, the heat generated during the machining should be reduced. The mean peak temperature generated during turning operation under different lubrication conditions is shown in figure 13.

Compared to turning under dry CRI condition, turning using PPO and MPPO exhibited 11.94% and 18.19% reduction in mean peak cutting temperature. As pongamia pinnata is a vegetable oil, it consists of large carbon chain with fatty acids [55] which helps in creating a thin oil film over the sprayed region. This thin oil is formed due to adsorption on the tool and chip surfaces. This lubricant film reduces friction and interaction [116], thereby reducing machining temperature. Effect of Ag nanoparticles did not drastically reduce cutting temperature. MPPO + 2% Ag lubrication caused 18.97% reduction in cutting temperature compared with CRI condition. Additive incorporation in vegetable oil lubrication poses to be advantageous as they help reduce tribological interactions. This is due to high volatile index [117] in Ag incorporated MPPO. Higher volatile index improves the thickness of the lubrication film, reducing machining temperature and tool wear. MPPO + 2% Ag nanoparticles exhibited maximum volatile index. Its presence in machining region forms a thicker lubricating film and retains its lubricity during volatile frictional interaction [118]. It helps to reduce machining temperature.

3.4. Surface roughness
Surface roughness of machined components is an indication of its quality and performance. Reduction in surface roughness is preferred as it enhances the life cycle of the end product. The surface roughness of the machined product depends upon the important machining parameters such as the depth of cut, machining speed and feed rate [119]. Apart from machining parameters, surface roughness of the machined components...
depends on tool wear rate. Surface of the machined components degrades and deteriorates when tool wear increases. The mean numerical surface roughness of Monel K 500 workpieces, machined under different conditions is shown in figure 14.

Surface roughness was recorded at 2.69 μm (maximum) on machining under dry CRI condition. Compared to machining under dry CRI condition, surface roughness was found to decrease by 17.1%, 26.7% & 28.2% on machining under PPO, MPPO and MPPO + 2% Ag lubrication conditions. It shows that additive incorporated MPPO lubrication produced the smoothest surface. Consistency of smoothness of surface depends upon the organic velocity of the vegetable oil lubricants. Variation in organic viscosity index of vegetable oil based lubricants occurs as kinematic viscosity and machining temperature changes. Hydration capability of vegetable oil lubricants increases when the quantity of esters [120] and complicated fatty acids increases [121]. Compared with other lubricating conditions, MPPO + 2% Ag nanoparticles exhibited better viscosity, even at elevated temperatures. Hence this condition enabled retention of lubricating oil on the machining surfaces & tool, throughout the machining duration. This condition prevented interference of the sheared workpiece to disturb and fall in front of the cutting tool. Throughout the turning operation, prevention of chaotic and sheared chips to interfere with cutting enables cleaner shear on the workpiece and smoother surface. The surface roughness value achieved using MPPO + 2% Ag lubricant was 1.93 microns. Even though the entire turning process was

![Figure 13. Mean peak cutting temperature under different lubrication conditions.](image1)

![Figure 14. Surface roughness of machines workpieces under different lubrication conditions.](image2)
lubricated, micro scratches occurred in the workpiece (monel K 500) surface. Presence of micro-tears and voids in the interacting surfaces cause reduction in the efficiency of the protective film [122]. This causes more interaction between tool and workpiece. Presence of Ag nanoparticles in the vegetable oil helped to considerably improve temperature dissipation and lubrication. Yet, in certain regions, due to surface defects in the workpiece, friction reduction was less, resulting in rougher surface. Due to solvency effect and competitive adsorption of the additives against vegetable oil molecules, lubrication properties tend to decline [123]. The workpiece (monel K 500) was used in the experiments in as-received condition. It was not subjected to surface treatment of pre processing, before subjecting it to machining under different lubrication conditions. The effectiveness of Ag nanoparticle incorporated lubricant in reducing the contact area of wear surfaces was lower in certain regions. It can be improved by subjecting the workpiece to heat treatment and burnishing.

3.5. SEM studies
The machined surfaces were subjected to microscopic evaluation using scanning electron microscopy. The samples for scanning electron microscope (SEM) evaluation were prepared by using standard metallurgical procedures. SEM images of monel K 500 workpiece base material and workpieces subjected to turning under different experimental conditions are shown in figure 15. SEM image of as-received monel K 500 base material is shown in figure 15(a). Fine and annealed grain structure was observed. Monel K 500 workpiece turned using TiAlN coated tungsten carbide insert is shown in figure 15(b). It shows erratic cracks and pits due to excessive frictional heating. Under dry turning conditions, globules were formed [124, 125] in the surfaces due to abrasive shear between the tool and the workpiece. SEM image of monel K 500 workpiece turned with PPO lubrication under MQL condition is shown in figure 15(c). Occurrence of cracks was less pronounced. Micro pits were identified and certain regions were smoother than the surface of the samples turned without lubrication. Eruptions were identified. This occurred due to non availability of the lubricant film of unprocessed pongamia pinnata oil at certain regions during turning operation. The SEM image of monel K 500 samples turned under MPPO lubrication under MQL condition is shown in figure 15(d). Micro cracks and micro voids were identified in the turned surface.

The surface grain deformation on the whole was lower than the surface turned using unprocessed oil. The SEM image of monel K 500 sample turned using MPPO + 2% Ag nanoparticles lubrication in MQL condition is shown in figure 15(e). The surface consisted of flake like deformations perpendicular to the turning direction. Low density pits were identified. The density of the pits was less than those observed while using PPO & MPPO. Globules were observed in certain regions. Presence of Ag nanoparticles in the lubricant caused reduction in surface deterioration.

3.6. EBSD studies
Using Electron Back Scattering Diffraction (EBSD) equipment, EBSD studies on Monel K 500 workpieces were conducted, before and after turning experiments. The average particle sizes were identified for each sample. EBSD images monel K 500 workpiece base material and those subjected to turning under different experimental conditions are shown in figure 16. Figure 16(a) shows EBSD image of base material monel K 500 in as-received condition. The grains were elongated and distributed with longer boundaries. The average grain size of the material was found to be 69.4 μm. EBSD image of monel K 500 subjected to turning with TiAlN coated tungsten carbide insert without lubrication (CRI) condition is shown in figure 16(b). Due to excessive heating, the grain sizes were found to decrease. Breakage, abrasion caused rupture of long grains to form smaller grains with shorter and irregular boundaries. On the surface of the workpiece material, 43.2% reduction in grain size was observed, compared to base material. This was due to grain refinement in the surface due to the induced frictional heat. In figure 16(c) EBSD image of the sample turned using PPO lubrication under MLQ condition was observed. Grain size reduction was witnessed, but not as much as CRI condition. Under PPO condition, the average grain size was reduced by 31.8% compared to the base material. This was due to the reduction in frictional heat and cutting forces generated in the machining region [126], due to the presence of PPO. EBSD image of the sample turned using MPPO lubrication under MQL condition is shown in figure 16(d). As MPPO lubrication ensured lower cutting forces and heat generation than PPO and CRI condition, grain size reduction was less pronounced. Monotonic decrease in average grain sizes were identified up on using PPO and MPPO condition. EBSD image of sample turned using MPPO + 2% Ag lubrication is shown in figure 16(e). Even though heat generated and cutting forces were lower, while using MPPO + 2% Ag lubrication, the average grain size was found to be lesser than PPO and MPPO condition. This was due to the interference of Ag nanoparticles in the lubrication film between the tool and workpiece [127].
3.7. XRD Studies

X-Ray diffraction (X-RD) studies were conducted on the turned monel K 500 workpieces under different lubrication conditions to identify the chemical modifications in the surface. The XR-D graphs of the various samples are shown in figure 17. X-RD graph of Monel K 500 base material is shown in figure 17(a). Ni peaks were identified at 43.67°, 53.29° & 76.05° 2θ values. These peaks indicated crystal lattice of (111), (200) & (220) respectively. XRD graph of TiAlN is shown in figure 17(b). Peaks were identified at 36.74°, 62.49° & 74.83° 2θ values, showing TiAlN at crystal lattice (111), (220) and (311) respectively. XR-D graph of tungsten carbide insert material is shown in figure 17(c). It shows WC at 32.41°, 35.26°, 48.49°, 63.24°, 65.14°, 72.36°, 75.49°, 76.32°, 84.23° 2θ and Co at 45.32° 2θ. X-RD graph of monel K 500 turned under PPO lubrication is shown in figure 17(d). Presence of WC at 32.39°, 63.29° 2θ and TiAlN at 36.44° 2θ was observed apart from Ni at 43.69°, 53.24° & 76.09° 2θ. XR-D graph of monel K 500 turned under MPPO lubrication is shown in figure 17(e). Presence of WC at 32.36° 2θ, TiAlN at 36.37°, 64.12° 2θ apart from Ni. XR-D graph of monel K 500 turned under MPPO + 2% Ag is shown in figure 17(f). Presence of WC at 32.29° 2θ, TiAlN at 36.32°, 64.56° 2θ, Ag at 40.89°, 63.24° 2θ was observed apart from Ni.
3.8. WC tool insert life

The machining tool is subjected to extensive damage due to abrasive wear, chemical erosion, diffusive wear, frictional melt wear. The wear mechanism depends upon the characteristics of the tool and the workpiece material. During turning, tool wear is affected due to chip formation. In this investigation, the primary reasons for tool failure was attributed to mean flank wear (MFW), maximum flank wear (MaxFW) and maximum notch wear (MaxNW). It was found that chemically processed MPPO oil considerably reduced cutting force and cutting region temperature. Machining was conducted at different lubrication conditions and tool life was calculated in terms of machining time with constant machining parameters. The variations in tool life under different lubrication conditions are shown in figure 18.

Compared to machining under CRI condition, PPO lubrication increased tool life by 36.23%. Presence of PPO’s lubricant during machining has considerably contributed to improvement in tool life. MPPO lubrication caused further improvement in tool life by 51.58%, compared to CRI condition. By chemical processing, presence of a thin film of lubricant in the workpiece tool interface was ensured, throughout the machining time.

![Figure 16. EBSD images of monel k 500 workpieces.](image)
**Figure 17.** XR-D graphs of (a) Monel K 500 base material, (b) TiAlN coating powder, (c) Tungsten carbide material, (d) Monel workpiece machined under PPO lubrication, (e) Monel workpiece machined under MPPO lubrication, (f) Monel workpiece machined under MPPO + 2% Ag lubrication.

**Figure 18.** Variations in tool life under different lubrication conditions.
Hence MPPO caused a considerable improvement in the tool life, compared to PPO. MPPO + 2% Ag nanoparticles lubrication ensured the highest tool life. 56.15% improvement in tool life was observed upon using MPPO + 2% Ag nanoparticles lubrication, compared to CRI. This was due to the additional lubrication.
and wear reduction induced by Ag nanoparticles. Improvement in cutting tool life helps to reduce the overall production and replacement costs.

### 3.9. Tool wear progression

Enormous friction developed between the tool and workpiece resulted in tool wear. Figure 19 shows the variations in flank wear. Figure 19(a) shows the variations in average flank wear (AFW) on conducting experiments using different lubricants. Figure 19(b) shows the variations in maximum flank wear (Max FW) on conducting experiments using different lubricants. Figure 19(c) shows the variations in maximum notch wear (Max NW) on conducting experiments using different lubricants.

Out of the three wear mechanisms considered, maximum notch wear was found to be common for all the experiments. Thermal stress induced by frictional heat generation caused tool wear. At the beginning stages of turning, a gradual increase in tool wear was observed. On continuous working, tool wear also increased. Compared to CRI condition (turning under dry condition without lubrication), tool wear was consistently lower for PPO condition. Further reduction in average flank wear, maximum flank wear and maximum notch wear was observed on turning under MPPO conditions. Addition of Ag nanoparticles helped in reducing wear. Turning under MPPO + 2% Ag exhibited 18.46% reduction in tool wear, compared to turning under CRI condition.

### 4. Conclusions

Hence, in this investigation an attempt was made to improve the performance of TiAlN coated tungsten carbide inserts using modified pongamia pinnata oil lubrication incorporated with Ag nanoparticles. The following conclusions were drawn.

1. Chemical treatment of pongamia pinnata oil and addition of Ag nanoparticles improved its lubricating properties.
2. Modified pongamia pinnata oil with 2% Ag nanoparticles inclusion resulted in higher kinematic viscosity, flash point, compared to other combinations. Formation of thin tribo-films due to inert and non reactive nature of Ag nanoparticles resulted in lower cutting forces and machining temperatures.
3. Presence of nanoparticles incorporated modified pongamia pinnata oil in monel K 500-cutting tool surface caused reduction in surface roughness.
4. The effect of pongamia pinnata oil and Ag nanoparticles on modifications in chemical and microstructural aspects of the machined tool and monel K 500 workpiece were studied. Improvement in machining performance and tool life was observed on using MPPO + 2% Ag nanoparticles.

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### Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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