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Effect of Coconut Oil-Based Cutting Fluid on Cutting Performance During Turning With Minimal Fluid Application

Robinson Gnanadurai Rengiah, Institute of Technology, University of Gondar, Ethiopia*
https://orcid.org/0000-0001-8969-7753

ABSTRACT

In the present work, an attempt was made to use vegetable oil as a cutting fluid during minimal fluid application to make the process more environmentally friendly. Coconut oil was selected as the vegetable oil in this study considering its availability, physical properties, and lubricating ability. The effect of newly formulated coconut oil-based emulsified cutting fluid on cutting performance during turning of hardened AISI 4340 steel with the minimal fluid application was investigated. It was observed that the coconut oil-based cutting fluid offered better cutting performance in terms of tool wear, surface roughness, cutting force, cutting temperature, and tool chip contact length when compared to mineral oil-based cutting fluid and raw coconut oil. It was also observed that the percentage of concentrate in the cutting fluid was to be maintained as 30% to achieve better cutting performance. The use of coconut oil-based cutting fluid holds promise as an environment friendly alternative for mineral oil-based cutting fluid.

KEYWORDS

Coconut Oil, Cutting Fluid, Hard Turning, Minimal Fluid Application, Tool Chip Contact Length

INTRODUCTION

Petroleum-based mineral cutting fluids produce environmental pollution due to the chemical breakdown of the cutting fluid at high cutting temperatures. Human operators when exposed to cutting fluids faced with health problems, such as skin cancer and inhalation of toxic mist in the work environments (Sokovic & Mijanovic, 2001; Sutherland et al., 2000). The use of cutting fluid may be eliminated by resorting to dry machining. But dry machining of hardened steel requires ultra-hard cutting tools and extremely rigid machine tools, as the process is devoid of the lubricating and cooling action of the cutting fluid (Klocke & Eisenblatter, 1997; Sreejith & Ngoi, 2000). Machining with the minimal fluid application is a viable alternative to dry machining, where a small quantity of cutting fluid is applied as a high-velocity pulsing jet at the cutting zone so that for all practical purposes it resembles dry cutting and at the same time free from the problems associated with large scale use of cutting fluids (Philip et al., 2001; Robinson & Varadarajan, 2012; Varadarajan et al., 2002a). The use of vegetable oil in metalworking applications may alleviate the harmful effects of mineral-based

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*Corresponding Author

cutting fluids. Around the world, many investigations are in progress to develop new biodegradable cutting fluids based on various vegetable oils available (Alves & Oliveira, 2006; Belluco & De Chiffre, 2004; Filho et al., 2017; Khan et al., 2009; Shashidhara & Jayaram, 2010). In the same manner, the environmental friendliness of the minimal fluid application scheme can be enhanced by replacing mineral oil-based cutting fluid with a vegetable oil-based cutting fluid. In the present work, an attempt is made to enhance the cutting performance of hard turning with the minimal fluid application by improving the rake face lubrication using coconut oil-based cutting fluid.

LITERATURE REVIEW

Vegetable oil-based cutting fluids are viable alternatives to mineral-based cutting fluids due to their properties like higher flash point, higher molecular weight, and dipolar nature. In addition, vegetable oils have others advantages such as very low volatility, good lubricity, and high viscosity index, as well as lower cost than synthetic oils. Vegetable oils are tri-esters of straight-chained, mostly unsaturated fatty acids with glycerol and have higher levels of biodegradability and much lower toxicity than conventional mineral or synthetic oils (Krahenbuhl, 2002).

Cetin et al. (2011) compared the performances of sunflower oil-based cutting fluid and canola oil-based cutting fluid with mineral oil-based cutting fluid during turning of AISI 304L austenitic stainless steel with carbide inserts. It was observed that the sunflower oil-based cutting fluid and canola oil-based cutting fluid offered better cutting performance in terms of surface finish and tool wear when compared to mineral oil-based cutting fluid.

A bio-based metalworking fluid from Jatropha oil was evaluated by Sani et al. (2019) in turning AISI 1045 medium carbon steel using cermet inserts under the MQL technique. The physicochemical characteristics of the Jatropha oil were enhanced by adding oil-miscible ammonium-based and phosphonium-based ionic liquid additives of different weight concentrations. Experimental results revealed that ionic liquids added to Jatropha oil improved the cutting performance due to their superior physical, chemical, and tribological properties and outperformed synthetic ester-based cutting fluid.

Effect of vegetable oil-based nano cutting fluids made from dispersion of nanosuspensions of molybdenum di sulphide in coconut oil, sesame oil, and canola oil was investigated by Rapeti et al. (2018) during turning of AISI 1040 steel with MQL. Three levels of base fluid, nanoparticle inclusions, cutting speed and feed rate are considered for multi-objective optimization based on Taguchi based Grey Relational. Optimal cutting performance obtained when work coconut oil+0.5% nano molybdenum sulphide applied at a cutting speed of 40 m/min and feed rate of 0.14mm/rev.

Wang et al. (2016) made an investigation on the grinding of GH4169 with seven different types of vegetable oil-based lubricating fluids namely soybean, peanut, maize, rapeseed, palm, castor, sunflower oil, and a commercial mineral oil using the MQL technique. Grinding performance was evaluated in terms of friction coefficient, specific grinding energy, grinding ratio (G-ratio) of the grinding wheel, surface morphology, and surface roughness. Compared with flood lubrication, vegetable oil as base oil provided a lower friction coefficient and specific grinding energy due to good lubrication properties. Among the seven vegetable oils, castor oil possessed good lubrication properties and resulted in the best surface morphology and minimum roughness value.

Xavior and Adithan (2009) studied the influence of coconut oil on tool wear and the attainable surface finish during the turning of AISI 304 steel with carbide tools. They compared the performance of coconut oil with two more cutting fluids namely an emulsion and neat cutting oil. The results indicated that coconut oil performed better than the other two cutting fluids in reducing the tool wear and improving the surface finish.

Krishna et al. (2010) compared the performance of cutting fluids consisting of nano boric acid suspensions in SAE-40 and that in coconut oil during turning of AISI 1040 steel with cemented carbide tool with a specification SNMG120408. Boric acid particles of 50 nm particle size were used in the suspensions. The percentage of suspension was varied at three levels namely 0.25%, 0.5%, and 1% by weight. It was observed that the flank wear and the surface roughness reduced considerably with the increase in the percentage of suspensions in cutting fluid. It was also observed that cutting fluid consisting of nanosuspension in coconut oil performed better than the one made of nanoparticles suspension in SAE-40 and a suspension consisting 5% by weight in coconut oil gave a better cutting performance in terms of cutting temperature, tool wear, and surface roughness.

Gajrani et al. (2019) performed turning experiments on hardened AISI H-13 steel with the green cutting fluid made from coconut oil. Green cutting fluid was synthesized by mixing raw coconut oil with food-grade emulsifiers, three oil extracts, and syrup of jaggery. Machining performance using the newly developed vegetable-based green cutting fluid with minimum quantity cutting fluid (MQCF) application technique was compared with flood cooling and dry machining. It was found that machining performance with the MQCF technique using the 1:16 emulsion composition of GCF outperformed other techniques. Results also showed that sticking and sliding zones length were reduced because of enhanced cooling and lubrication of high pressurized MQCF mist at the tool-chip sliding region.

Based on the review of the literature (Adhvaryu & Erhan, 2002; Joseph et al., 2007), the properties of coconut oil is summarized in comparison with other vegetable oil and shown in Table 1.

As coconut oil is 100% biodegradable, it does not possess any problems connected with the disposal. It is highly environment and people friendly and causes no skin problems to workers exposed to it. It has got high oxidative and thermal stability. In the present work, it was decided to formulate a cutting fluid using coconut oil as the base by considering its availability, physical properties, and lubricating ability. A review of research articles particularly on coconut oil-based cutting fluid to date revealed that special formulation used for the development of coconut oil-based cutting fluid and its detailed characterization with different compositions was not found in any literature. Furthermore, research efforts on studying the effect of this type of cutting fluid on cutting performance were done mostly with conventional machining and machining with Minimal Quantity Lubrication (MQL) methods, and no literature was found with the minimal fluid application method. Hence, in this research work, an attempt was made to develop a cutting fluid based on coconut oil and to study its effect on cutting performance during hard turning with Minimal fluid application. This research work consisted of three phases. In the first phase, coconut oil-based cutting fluid was formulated and its properties were ascertained. In the second phase, an experimental investigation was done to study the cutting performance of the formulated cutting fluid in comparison with the conventional mineral oil-based cutting fluid. Finally, the influence of the composition of coconut oil-based cutting fluid on tool wear was investigated.

Table 1. Properties of coconut oil are compared with other vegetable oil

Properties	Coconut Oil	Castor Oil	Rapeseed Oil	Soyabean Oil	Jatropha Oil
Kinematic Viscosity @40 ºC (cst)	27.6	220.6	45.6	32.93	47.48
Kinematic Viscosity @100 ºC (cst)	5.9	19.72	10.07	8.08	8.04
Viscosity Index	165	220	216	219	208
Density(g\cm^3) @ 15 ºC	0.926	0.9666	0.9456	0.928	0.923
Flash Point(°C)	225	250	240	240	240
Pour Point(°C)	20	-27	-12	-9	0

FORMULATION OF COCONUT OIL-BASED CUTTING FLUID

The work reported by Paul et al. (2016) and Varadarajan et al. (2002b) were used as the basis for formulating a cutting fluid with coconut oil as the base. The formulation acted as oil in water emulsion. Coconut oil-based concentrate was formulated by mixing coconut oil with Oleic acid and Triethanol Amine in the ratio of 2:2:1 respectively. Oleic acid is an unsaturated fatty acid that is used as an emulsifying or solubilizing agent. Besides serving as an agent for improving the lubricity of the cutting fluid, it also acts as the friction modifier for lowering the friction coefficient. In water soluble cutting fluids, Triethanol Amine is used to provide the alkalinity needed to protect against rusting and it acts as an anti-oxidant. It also controls the evaporation rate of water in cutting fluid.

40 cc of coconut oil was taken in a beaker and 40 cc of Oleic acid was added to it slowly in four steps. The mixture was stirred thoroughly using a mechanical stirrer and when the mixture became a homogeneous liquid, 20 cc of Triethanol Amine was added and stirred thoroughly to get a homogeneous mixture that can dissolve in water in all proportions and functions as oil in water emulsion.

Emulsion Stability Test as Per IS 1448

The oil in water emulsion prepared out of the concentrate was subjected to an emulsion stability test as per IS 1448 specification (1981). Initially, a $CaSO_4$ solution of total hardness equivalent to 405 ppm was prepared by dissolving 0.688 gm of $CaSO_4$ per liter of distilled water. Next, eight emulsion samples were prepared as shown in Table 2. The requisite quantity of the concentrate was taken in a hypodermic syringe. The corresponding quantity of water was taken in a 150 ml measuring flask which was kept stirred using a stirrer so that a vortex was formed. The oil was poured into the vortex thus formed. The stirring was continued for 2 more minutes after the last drop of oil was transferred. All the samples were allowed to stand for 48 hours and evaluated based on separation, frothing, homogeneity, and coloration. There was no trace of oil separation in any one of the eight samples prepared and this is an indication of the high stability of emulsion prepared as per IS 1448 specifications.

Characterization of the Coconut Oil-Based Cutting Fluid

The coconut oil emulsions with 10% (10% concentrate + 90% water), 20%, 30%, and 40% concentrate by volume were prepared and characterized to ascertain its chemical nature and for comparing its properties with mineral-based cutting fluid. Properties such as density, viscosity, pH value, refractive index, and thermal conductivity were evaluated experimentally. Density and pH value was measured using the specific gravity bottle having volume 5 cm^3 and pH meter respectively. Refractive index was determined with Abbe's refractometer (Make: Roslane Meditech) and viscosity at 40 °C were measured using Brookfield DV-E viscometer. Thermal conductivity was measured using KD2 Pro thermal properties analyzer. The measured values of these properties are presented in Table 3 in comparison with mineral oil-based cutting fluid and raw coconut oil.

EXPERIMENTAL PROCEDURES

It was decided to evaluate the feasibility of using the formulated cutting fluid for hard turning with minimal fluid application. Cutting experiments were conducted on a Kirloskar Turn master- 35 lathe.

Table 2. Emulsion ratios and the corresponding proportions of water and concentrate

Sample No.	1	2	3	4	5	6	7	8
Emulsion ratio	5:1	10:1	15:1	20:1	25:1	30:1	50:1	80:1
Test water (ml)	150	200	180	200	200	180	200	240
Concentrate (ml)	30	20	12	10	8	6	4	3

Table 3. Physical properties of different cutting fluids

Cutting Fluid Composition	Density (kg/m³)	Viscosity at 40° (Cetipoise) 30 rpm	PH value	Refractory Index	Thermal Conductivity (W/mK)
10% Coconut Oil emulsion	894.37	14.0	7.49	1.336	0.391
20% Coconut Oil emulsion	891.81	20.5	7.59	1.348	0.390
30% Coconut Oil emulsion	889.66	63.2	7.67	1.36	0.390
40% Coconut Oil emulsion	887.61	78.5	7.73	1.372	0.387
Mineral Oil-based Cutting fluid	890.95	12.8	7.71	1.506	0.388
Raw coconut oil	924.27	26.8	7.8	1.448	0.321

AISI 4340 steel with a hardness of 45 HRC was used as the work material. Bars of 70 mm in diameter and 350 mm in length were used in this investigation. Multicoated hard metal inserts with sculptured rake face geometry with a specification SNMG 120408 of Tague Tec were used in the investigation. The tool holder had a specification of PSBNR 2525M12. The cutting fluid concentrate formulated was added to water to obtain the coconut oil-based cutting fluid. Mineral oil-based water-soluble cutting fluid was prepared from MAK Sherol B cutting oil. An emulsion ratio of 20:1 is selected for both coconut oil-based and mineral oil-based cutting fluids for comparing their performance during machining. The minimal fluid applicator was used to apply cutting fluid in the form of a narrow pulsing jet at the tool work interface. Based on the preliminary experiments carried out by the author (2012), fluid application parameters were selected and kept at values shown in Table 4. Cutting experiments were conducted to compare the performance of the coconut oil-based cutting fluid formulation with a commercial mineral-based cutting fluid and pure coconut oil during hard turning with minimal fluid application. This was accomplished by conducting a variable speed test, a variable speed test, and a tool life test.

The depth of cut was maintained as 1.25 mm and the time of cut was maintained as 60 seconds for the variable speed test and the variable feed test. The cutting force was measured using a Kistler tool force dynamometer, surface roughness was measured using a stylus type surface meter (Perthen Make), and tool flank wear and tool chip contact length were measured using a tool maker's microscope. A tool-work thermocouple was used to measure the cutting temperature at the tool tip using an extrapolative technique (Varadarajan et al., 2000) based on finite element analysis. During the variable speed test, feed was kept at 0.1 mm/rev, depth of cut was kept at 1.25 mm and the cutting velocity

Table 4. Values of fluid application parameters kept constant

Fluid application parameter	Values
Rate of fluid application, Q	5 ml/min
Pressure of the fluid injector, P	80 Bar
Frequency of pulsing, N	300 pulses/min
Percentage of concentrate, C	20%+rest water

was varied from 80 to 120 m/min at five intervals. The cutting velocity was kept at 80 m/min, depth of cut was kept at 1.25 mm, and the feed was varied from 0.04 to 0.08 mm/rev at five equal levels during the variable feed test. During the tool life test cutting velocity was kept at 80 m/min, feed at 1 mm/rev, and depth of cut at 1.25 mm. Figure 1 presents the photograph of the experimental setup.

RESULTS AND DISCUSSION

Figures 2 to 5 present the variation of cutting force, cutting temperature, surface roughness, and tool chip contact length as a function of cutting velocity. The variation of cutting force, cutting temperature, surface roughness, and tool chip contact length with feed are presented in Figures 6 to 9 respectively.

Low cutting forces and tool-chip contact lengths were observed when raw coconut oil was used as the cutting fluid when compared to that observed during the application of mineral oil-based cutting fluid and the coconut oil-based cutting fluid (Figures 2, 5, 6, and 9). Coconut oil has high thermal stability and the long-chained molecules of coconut oil are dipolar in nature and can create a dense, homogeneous, and strong lubricating film in the contact zones. The film can absorb high

Figure 1. Photograph of the experimental setup

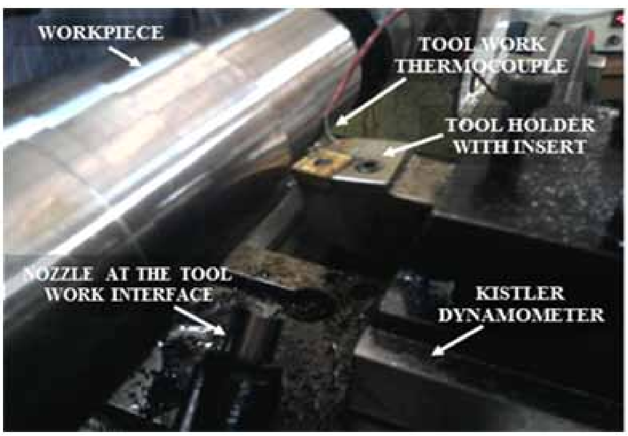


Figure 2. Variation of cutting force as a function of cutting velocity for different cutting fluids

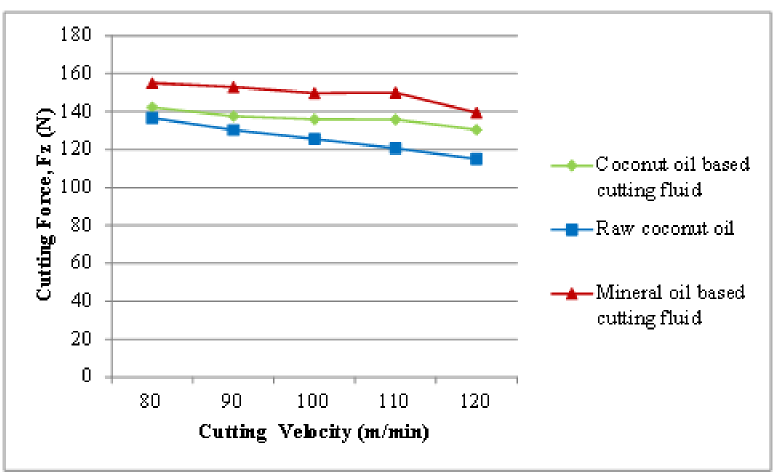


Figure 3. Variation of cutting temperature as a function of cutting velocity for different cutting fluids

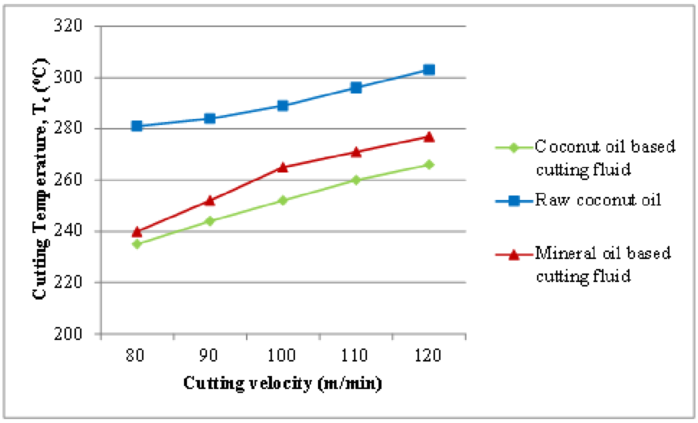


Figure 4. Variation of surface roughness as a function of cutting velocity for different cutting fluids

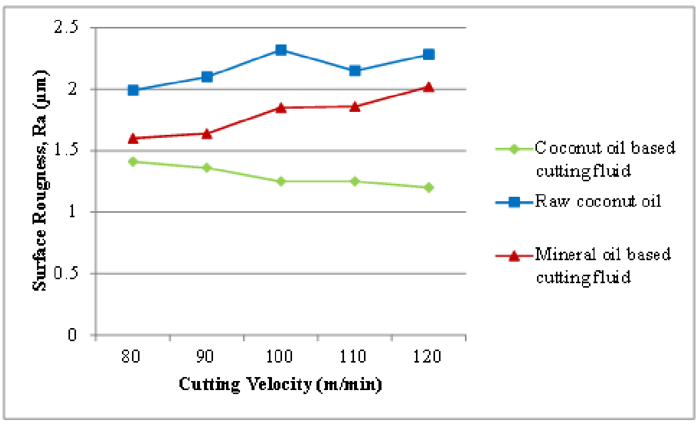


Figure 5. Variation of tool chip contact length as a function of cutting velocity for different cutting fluids

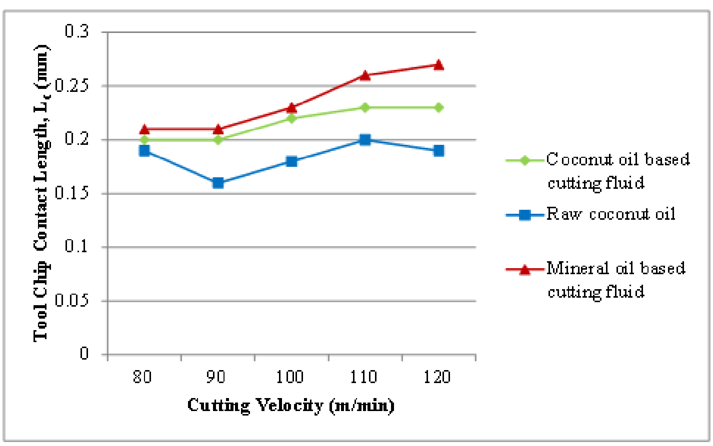


Figure 6. Variation of cutting force as a function of feed rate for different cutting fluids

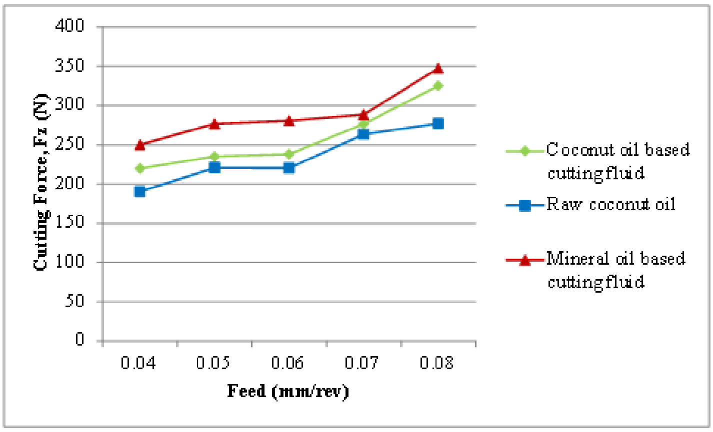


Figure 7. Variation of cutting temperature as a function of feed rate for different cutting fluids

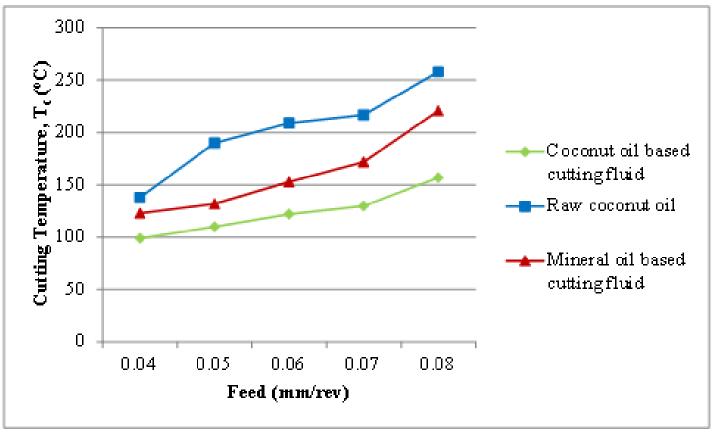


Figure 8. Variation of surface roughness as a function of feed rate for different cutting fluids

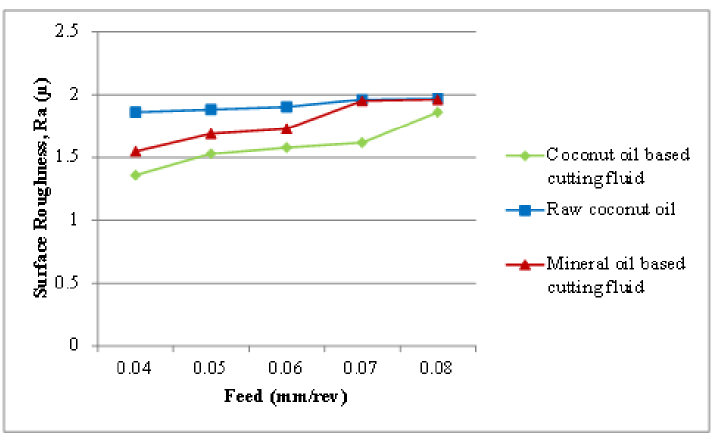
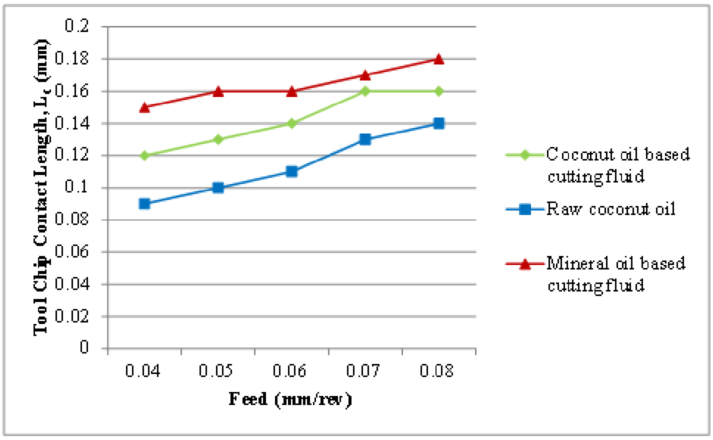


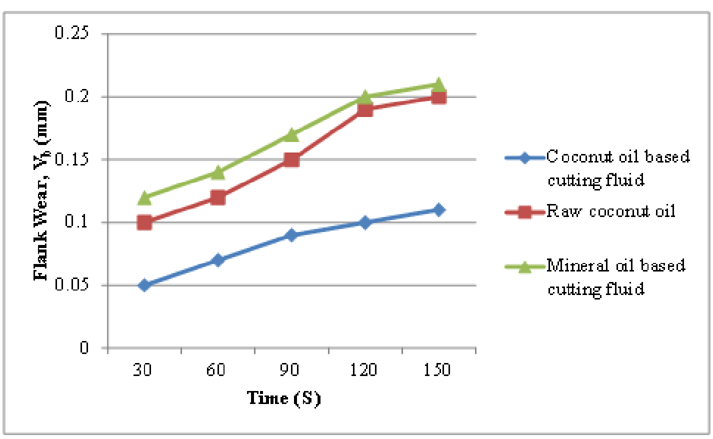
Figure 9. Variation tool chip contact length as a function of feed rate for different cutting fluids



pressure and offer better lubrication resulting in a reduction of tool-chip contact length and cutting force (Shashidhara & Jayaram, 2010). As evident in the results shown in Table 3, raw coconut oil has a higher viscosity which suggests that raw coconut oil possesses better lubrication ability. But it was found that raw coconut oil could not bring forth low cutting temperatures as shown in Figures 3 and 7. This is because the lower thermal conductivity of raw coconut oil causes it to have a poor cooling ability (Table 3). It was observed that the performance of mineral oil-based cutting fluid was at par with that of coconut oil-based cutting fluid in this aspect as both of them have comparable thermal conductivity as evident in Table 3.

It was clear from Figures 3, 4, 7, 8, and 10 that the application of coconut oil-based cutting fluid lowered cutting temperature, surface roughness, and tool wear. It was due to the better lubrication and cooling ability of the coconut oil-based cutting fluid when compared to that of mineral oil-based cutting fluid on account of its structure and thermal stability. Tool wear is a temperature-activated phenomenon which in turn affects surface roughness. As the coconut oil-based cutting fluid was effective in reducing the cutting temperature, there was a decrease in tool wear and surface roughness. This finding is similar to the observations made by Xavior and Adithan (2009). The superiority of

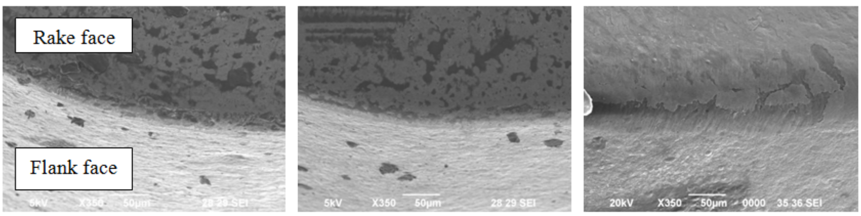
Figure 10. Variations of flank wear with time during turning with the minimal fluid application using mineral oil-based cutting fluid, coconut oil-based cutting fluid, and raw coconut oil



coconut oil-based cutting fluid was established further by the results of the tool life test. The tool wear was the least during the application of coconut oil-based cutting fluid during the whole length of the tool life test (Figure 10). Moreover, SEM photographs (Figure 11 (a), (b), and (c)) of worn inserts indicated less damage to the cutting edge when coconut oil-based cutting fluid raw coconut oil and mineral oil-based cutting fluid were used.

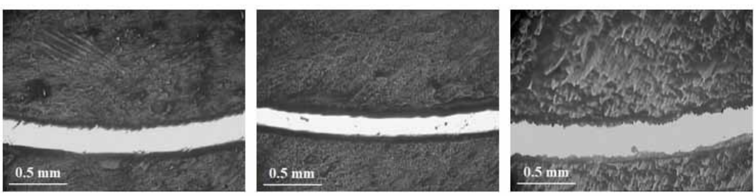
Chip micrograms during the application of different cutting fluids are shown in Figure 12. The thickness of the chips collected during experiments was measured using the tool maker's microscope and is presented in Table 5. The lowest chip thickness (ie, 0.15 mm) was observed with raw coconut oil followed by coconut-based cutting fluid. It was also observed that the chip sections contained fewer signs of distortions when the raw coconut oil was used as well as when coconut oil-based cutting fluid was used. Chip thickness is an index of the frictional conditions at the tool chip interface. Better the rake face lubrication, thinner will be the chips and lesser will be the deformation and damages on its cross section.

Figure 11. SEM photograph of tool wear when (a) coconut oil-based cutting fluid (b) raw coconut oil was used as cutting fluid (c) mineral oil-based cutting fluid were used. (V=80 m/min, f=1 mm/rev, d=1.25 mm)



(a) (b) (c)

Figure 12. Chip microgram during the application of (a) coconut oil-based cutting fluid (b) raw coconut oil (c) mineral oil-based cutting fluid (V=80 m/min, f=1 mm/rev, d=1.25 mm) (Magnification 100 X)



(a) (b) (c)

Table 5. Thickness of chips collected

Type of cutting fluid	Chip Thickness (t_c) (mm)
Coconut oil-based cutting fluid	0.19
Raw coconut oil as cutting fluid	0.15
Mineral oil-based cutting fluid	0.26

Effect of the Percentage of Concentrate on Tool Wear

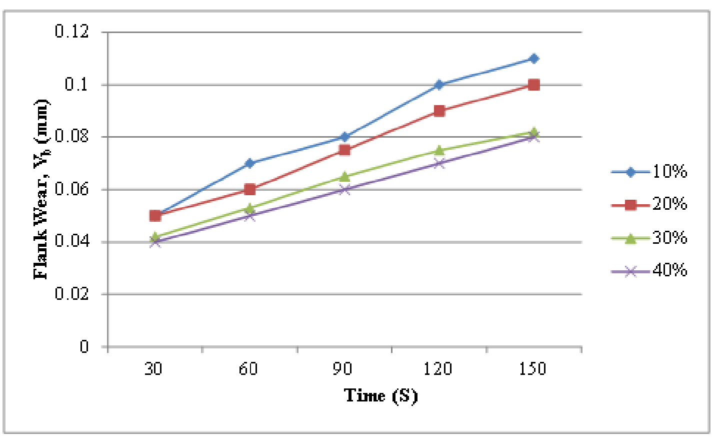
It was decided to study the effect of the percentage of concentrate in the cutting fluid on tool wear. Accordingly, the percentage of the concentrate in water was varied at four levels such as 10%, 20%, 30%, and 40% by volume. The fluid application parameters were maintained at values as shown in Table 4. Flank wear was measured at an interval of 30 seconds using a tool maker's microscope and the results are presented in Figure 13.

The highest tool wear values are observed when the cutting fluid consisted of 10% concentrate and the rest water. When the cutting fluid composition was at level 2, ie 20% concentrate and the rest water, there was a reduction in the tool wear in the whole range. The tool wear characteristics marked still lower values when the cutting fluid composition was kept at level 3 (ie, 30% concentrate + 90% water). But when the percentage of concentrate was further increased to 40% there was only a marginal reduction in the wear characteristics. Tool wear is decided by the combined effect of cooling and lubricating abilities of the cutting fluid. When the percentage of concentrate is more, the lubricating ability of the cutting fluid increases but its cooling ability comes down as the percentage of water is reduced. For achieving high cooling ability, cutting fluid must have high thermal conductivity and for better lubrication ability, cutting fluid must have high viscosity. The cutting fluid offers its best when there is a good balance between its lubricating and cooling abilities. From the properties of cutting fluids summarized in Table 3, it appears that coconut oil-based cutting fluid with 30% concentrate has a good balance between lubricating as well as cooling ability. When the percentage of the concentrate was increased to 40% there was not much improvement in the wear characteristics due to the poor cooling ability of the tool as its thermal conductivity is found to be lower. Hence the percentage of concentrate in the cutting fluid may be maintained at 30% which will lead to better tool wear characteristics and at the same time can fetch a saving of 10% in the use of concentrate.

CONCLUSION

A cutting fluid was formulated with coconut oil as the base which can act as an oil in water emulsion during turning of hardened AISI 4340 steel with minimal fluid application. The performance of the new cutting fluid was compared with that of conventional mineral oil-based cutting fluid and raw coconut oil by conducting machining experiments. From these experiments, the following observations are made:

Figure 13. Variations of flank wear with time for different percentages of cutting fluid concentrate in water



1. Coconut oil-based cutting fluid offered better cutting performance in terms of low tool wear, low surface roughness, low cutting force, low tool chip contact length, and low cutting temperature when compared to mineral oil-based cutting fluid and raw coconut oil.
2. Percentage of concentrate in the coconut oil-based cutting fluid can be maintained as 30% to achieve better cutting performance due to its effective cooling and lubrication property compared to other compositions.
3. Experimental results indicated that 30% coconut oil-based cutting fluid brought forth, a cutting force of 131 N, a cutting temperature of 266 °C, a surface finish of 1.17 µm, and a tool chip contact length of 0.23 mm when machining performed using a cutting speed of 120 m/min, feed rate of 0.1 mm/rev and depth of cut of 1.25 mm.
4. Coconut oil-based cutting fluid is environmentally as well as human friendly and does not need petroleum products such as mineral oils which are to be imported.

Studies on microbial contamination and biodegradability are required to find the suitability of the coconut oil-based cutting fluid for its wide range of applications in the industry. For successful implementation of the proposed vegetable oil-based cutting fluid, it is essential to carry out a comprehensive cost analysis. These may be proposed as the future scope of this work.

CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this paper.

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Robinson Gnanadurai Rengiah is working as an Assistant Professor in the Department of Mechanical Engineering, Institute of Technology, University of Gondar, Ethiopia. He received his Ph.D. from Karunya University, Coimbatore, India. His area of research is machining with minimal cutting fluid. His research papers are published in several international journals and conference proceedings.