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Comparative Analysis of Selected Animal and Vegetable Oils Suitability in Machining of Plain Carbon Steels

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ABSTRACT

Due to the alarming rate in public awareness on environmental issues, there has been growing demand for biodegradable materials which has opened an avenue for using vegetable and animal oils as alternatives to petroleum-based polymeric materials in the market, most especially in machining operations. Thus, research on biodegradable functional fluids has emerged as one of the top priorities in lubrication, due to their applicability in many diverse areas. In this quest, there is need to conduct machining trials to determine the suitability of these oils in metal cutting (turning) operations of plain carbon steels. This study investigate the effect of the selected cutting fluids on certain parameters like machine removal rate (MRR), machining time, tool wear and spindle power consumption, etc. under different machining combination in turning operations of plain carbon steels obtained from universal steel Ikeja, Nigeria, using 150 x 10 HSS cutting tool. The selected oils purchased from Ogunpa market in Ibadan, Nigeria, were sieved to remove any foreign particles or dirt. The solution; water, based-oil, and emulsifier (to allow thorough mixing of water and oil without separation), were mix at an elevated temperature of 55^{0}C in a proportion 4:1:3. Experimental results clearly showed that Conventional cutting fluid might be replaced with Non-conventional cutting fluids (vegetable and animal based) as they give better performance. With slight modifications and deliberate but careful alterations in some of the components of such oils, even better performing cutting fluids could be obtained.

Keywords-- Plain Carbon Steels, Vegetable - Animal Oils, Conventional Fluids, Machining Parameters

I. INTRODUCTION

Steels are classified on the basis of their carbon content as their major alloying element is carbon [1]. Invariably, they are metal alloys with the combination of two elements, iron and carbon. Other elements (traces) present are too small in quantity to affect its properties. Carbon steel or plain carbon steels are those containing 0.1-0.25% [2]. The trace elements allowed in plain-carbon steel are: manganese (1.65% max), silicon (0.60% max), and copper (0.60% max). Plain carbon steels are widely used for many industrial applications and manufacturing on account of their low cost and easy fabrication [1].

However, the machinability of ferrous alloys such as plain carbon steel is sometime a difficult task; some of the characteristics that caused this are high strength, low thermal conductivity, high ductility and high work hardening tendency. Poor surface finish of the work materials, high cutting force and high tool wear are generally observed when machining these materials.

It has also been observed that whenever a tool penetrates into the work piece and removes the material in the form of chips, it consumes a major portion of energy. The greater the energy consumption, the greater are the temperature and frictional forces at the tool chip interface and consequently, the higher will be the tool wear [3]. It is therefore imperative that effective control of heat generated in the cutting zone during metal removal is crucial to ensuring good work piece surface quality [4].

Although as discussed in many literatures, the performance of the machining is based on the type of cutting fluid and the method of application. Hence, vegetable oil-based and animal oil-based metal working fluids (MWFs) are used to eliminate the effect of heat generation, corrosion and friction on both the tool and the workpiece [5], provide lubrication between chip tool interfaces and flush away chips from machining of steel alloys and improve surface finish of the work material [6].

According to [7], mineral oils have been in use as the traditional source of cutting fluids in machining a number of metals and alloys because of their suitable lubricating properties on both the workpiece and the cutting tools (as reported in [8][9]. Mineral oils are petroleum based cutting fluids, which are easily obtainable in markets and are relatively excellent coolants. However, there are now myriad of challenges posed by using such oils as lubricants in most of today's application. Their continuous usage in machining will pose environmental contamination and health problems to operators [7]. Growing environmental concerns such as renewability, biodegradability, safety and health of operators demand serious attention. For this reasons, it is necessary to see how suitable animal and vegetable oil based cutting fluids are in machining operations.

Thus, this work is aimed at comparing and analyzing the suitability of some selected animal and vegetable oils in the turning operation of plain carbon steels using two (2) vegetable and two (2) animal oils as potential cutting fluids in machining operations; and investigating the effect of the selected cutting fluids on certain parameters like tool temperature, tool life, spindle power consumption, tool wear, workpiece roughness and chip formations etc.

II. METHODOLOGY

Materials

Five (5) pieces of plain carbon steel rods (AISI 1028), high speed steel tool (150 x 10 HSS), emulsifier (0.5 M sodium lauryl sulphate + nitrosol + sodium tripolyphosphate + sulphonic acid + calcium carbonate), Lard Oil, Tallow Oil, Palm Oil (Red oil), Palm Kernel Oil (PKO) and Conventional Mineral Oil based cutting fluids were used as the primary materials in this present study. The materials were selected based on their properties. The steel samples were obtained from Universal Steel Limited, Ogba, Ikeja-Lagos State, Nigeria. The results of the chemical compositions of those steel samples obtained via an optical electron spectrometer (OES) are presented in table 2.1.

A. **Lard Oil**: Lard is a *pig fat* in both its *rendered* and unrendered forms. It is obtained from any part of the pig where there is a high proportion of *adipose tissue*. It can be rendered by steaming it or boiling it in water and then separating the insoluble fat from the water, or by the use of dry heat. It is commonly used in many cuisines around the world as a *cooking fat* or shortening, or as a spread similar to butter. However, Lard Oil is colorless or yellowish oil expressed from Lard, used chiefly as a *lubricant for cutting tools*. Its smoke point is 190^0C or 374^0F.
B. **Tallow Oil:** This is a rendered form of beef or mutton fat. It is solid at room temperature. Unlike suet, tallow can be stored for extended periods without the need for refrigeration to prevent decomposition, provided it is kept in an airtight container to prevent oxidation.
C. **Palm Oil:** The selected vegetable oil (Palm oil) is an important and versatile vegetable oil which is used as a raw material for both food and non-food industries particularly soap and detergent industries. It is obtained from the fruit (both the flesh and the kernel) of the oil palm tree. Oil palms are highly efficient oil producers, with each fruit containing about 50% oil. It is also the cheapest vegetable oil in all the vegetable oils. Bio-based oils have a much higher flash point than petroleum. Flash points go down as viscosity of oils is reduced [4].
D. **Palm Kernel Oil:** These are the oils made from plants such as palm, soybean, sunflower, rapeseed, pongamia pinnata and coconut etc. Bio lubricants are generally considered as lubricants with high biodegradability as well as low human and environmental toxicity [10]. However palm kernel oils are obtained from palm kernel.
E. **Mineral Oils:** These are petroleum based products used as cutting fluids in machine operations. Mineral oils have been in use as the traditional source of cutting fluids in machining a number of metals and alloys because of their suitable lubricating properties on both the workpiece and the cutting tools [8][9].
F. **Emulsifier or Additives:** An emulsifier or emulsifying agent is a compound or substance which acts as a stabilizer for emulsions preventing liquids that ordinarily do not mix from separating. The word comes from the Latin word meaning "to milk", in reference to milk as an emulsion of water and fat. Another word for an emulsifier is an *emulgent*.

Equipment

The lists of equipment required for the work include: Variable speed centre lathe, Optical electron spectrometer (OES), Digital thermocouple, Stop watch, Digital weighing balance, Vibration Meter (SD Card Data Logger-VB 8206SD), Magnifying glass (SANDVIK Coromant- Tool Wear), USB Data Logger, Computer system, Universal Tensile machine, Hardness Test machine, AVERY Impact Test machine, Bunsen Burner, Stirrer and Aluminium pot.

Method

This work was conducted based on the following principal approaches:

1. Spectrochemical Analysis
2. Cutting fluids' preparation
3. Machining
4. Mechanical Testing
5. Experimental Analysis/Parametric Studies

1. Spectrochemical Analysis of Workpiece Material

Chemical analysis of the steel sample was carried out using an optical electron spectrometer (OES) at the Universal Steels Limited, Ogba, Ikeja-Lagos State. The result obtained is presented in Table-1.

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Table - 1: Spectrochemical Analysis of Workpiece Material

Element	C	Si	Mn	S	P	Cr	Ni	Cu
%Composition	0.2800	0.2070	0.6740	0.0310	0.0280	0.0710	0.0870	0.1370
Element	Nb	Al	B	W	Mo	V	Ti	Fe
%Composition	0.0001	0.0020	0.0001	0.0001	0.0001	0.0001	0.0170	98.4660

2. Cutting Fluids' Preparation

Five different cutting fluids, that is, Lard Oil Cutting Fluids (LOCFs), Tallow Oil Cutting Fluids (TOCFs), Palm Oil Cutting Fluids (POCFs), Palm Kernel Oil Cutting Fluids (PKOCFs) and Conventional Mineral Oil based Cutting Fluids (MCFs) shown in fig.-1 (a-e) were purchased in a local market in Ibadan, Oyo State, Nigeria. The local oils were sieved to remove any foreign particles or dirt. The additives (emulsifier) were mixed in the proportion shown in Table-2.

The emulsifier (0.5 M sodium lauryl sulphate + nitrosol + sodium tripolyphosphate + sulphonic acid + calcium carbonate) was added to prevent separation of water from oil. The mixing was carried out at an elevated temperature of 55°C as used by [3] and [7].

Table - 2: Constituents of Cutting Fluids

Cutting Fluids	% Water	% Additives	% Base Oil	Mixture Ratio	Total (%)
LOCFs	52.5 (105cl)	12.5 (25cl)	35 (70cl)	4:1:3	100
TOCFs	52.5	12.5	35	4:1:3	100
POCFs	52.5 (105cl)	12.5 (25cl)	35 (70cl)	4:1:3	100
PKOCFs	52.5	12.5	35	4:1:3	100
MCFs (As purchased)	100	-	-	-	100

(a) Lard Oil

(b) Tallow Oil

(c) Palm Oil (Red Oil)

(d) Palm Kernel Oil (PKO)

(e) Mineral Oil Cutting Fluid (MCF)

Fig. - 1: Cutting fluids

3. Machining

The machining process involved the following:

a) Workpiece Materials and Cutting Tools: plain carbon steel was used as a workpiece material. The sample has a length of 100mm with ϕ16. The workpieces from the same batch were used in the experiments. The cutting tool used was high speed steel tool (150 x 10 HSS). It is used in form of tool tip or inserted cutter teeth.

Fig. - 2: HSS Cutting Tool

b) Turning Process: The turning experiments were carried out on a variable speed centre lathe (Model AMI-STUDENT-175-1000MM). Turning of the steel samples was done at an ambient environment of 28.5°C. Table 2.3 shows the level of experimental parameters used for the machining.

In addition, the selected cutting speed and feed rate for the machining operation are presented in fig. - 3.

During the machining operation, each of the selected cutting fluids was applied to each workpiece through a double hose by flooding. Temperature of each steel sample was taken during turning with the aid of a portable digital thermocouple (handy-type). The digital thermocouple shown in fig. -4 has a sensor that senses the temperature of the cutting tool and the workpiece at far distance or proximity over time during machining operation. The turning process was interrupted after every experiment and value of the wear was taken.

Table - 3: Level of Experimental Parameters

Machining Parameters	Cutting speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)
Independent Variables	165	0.22	1.0
	110	0.44	2.0
	73	0.11	3.0

Fig. -3: (a) Selected Cutting Speed (rpm) (b) Selected Feed Rate (mm/min)

Fig. -4: Portable Digital Thermocouple (Handy-Type)

Again, spindle vibration was measured before, during and after machining of each workpiece (sample) using a Vibration Meter (SD Card Data Logger-VB 8206SD) shown in fig. -5. It has the capacity (inform of sensor) to record the minimum and maximum spindle vibration over time.

Fig. -5: Portable Digital SD Card Data Logger Vibration Meter (VB 8206SD)

c) Tool Wear Measurement: Flank wear was measured at 50x magnification using Magnifying glass (SANDVIK Coromant) shown in fig. -6. At the end of each turning process, the flank wear of the inserted tool was measured via a graduation scale embedded in the magnifying glass, and its value was recorded.

Fig. -6: Magnifying Glass (SANDVIK Coromant)

4. Mechanical Testing

The prepared plain carbon steel samples were turned into standard gauge length for tensile and impact test according to ASTM E8 and D 256 respectively, on the centre lathe machine. This was carried out at the Centre for Energy Research and Development (CERD), as well as Material Laboratory of the Department of Material Science and Metallurgical Engineering, all in OAU, Ile-Ife, Osun State. The tensile, impact and hardness tests were carried out on the samples.

5. Analysis/ Parametric Studies

In this present study, the performances of animal oil based (lard and tallow oils) cutting fluids and vegetable cooking oil (palm and palm kernel oils) based cutting fluids were examined and compared to the conventional mineral oil based cutting fluids during machining operation of the selected plain carbon steels. The effect of these oils as cutting fluids on independent variables like cutting speed (rev/min), feed rate (mm/rev) and depth of cut (mm) under different dependent variables such as temperature of the work pieces, tool life, spindle power consumption, as well as their chip formation rates were examine.

a) **Spindle Power Consumption (SPC):** The spindle power consumptions were obtained with the aid of the logger shown in fig.-7. The logger has the capacity to read the current and the voltage of the milling machine used.

$$SPC = Current(A) * Voltage(V)$$

$$P = I * V \ (Watts) \qquad (2.1)$$

Fig. -7: Logger Connected to the Centre Lathe via Electric Motor and Computer System

b) **Tool life:** This is the period of time a tool cut satisfactorily to the time it requires re-grinding due to failure.

If the tool life values obtained from the experimental data are plotted on a natural log-log graph of cutting speed versus tool life, the resulting relationship is a straight line expressed in equation form called the Taylor tool life equation [11]:

$VT^n = C$ (2.2a)

Where v = cutting speed; T = tool life; n and C are constants, whose values depend on cutting conditions, work and tool material properties, tool geometry, feed, depth of cut, and the tool life criterion used. These constants are well tabulated and easily available.

$logV + nlogT = logC$ (2.2b)

$logV = -nlogT + logC$ (2.2c)

Also from equation of a straight line;

$y = mx + c$ (2.2d)

Relating equation 2.2(c) to 2.2(d),

$n = \text{slope}; C = \text{intercepton the logV axis}$

The negative (-ve) sign in equation 2.2(c) shows a fall in logV against logT.

Thus, an expanded version of Taylor's tool life equation can be formulated to include the effect of feed, depth of cut and even work material properties.

$VT^n * S^y * D^x = C$ (2.2e)

Where V= cutting speed, T= tool life, D = depth of cut, S= feed rate; x and y are determined experimentally, they are arranged according to the order of importance. n and C are constants.

Using these parameters, equation 3.3(e) can be re-written as: $T = C^{\frac{1}{n}} * V^{\frac{-1}{n}} * S^{\frac{-y}{n}} * D^{\frac{-x}{n}}$ (2.2f)

c) **Machine Removal Rate (MRR):** This is the volume of the unwanted materials (chips) removed from the machined in a specified period of time

Note: Conversion formulae used for converting MRR (gm/sec) into MRR (mm3/min.) according to [4] is:

$MRR = (w_1 - w_2)/t \ \ gm/sec$ OR

$$MRR = \frac{[(w_1 - w_2)/t]}{Density\ of\ AISI1028\ Steel\ (kg/m^3)} * 1000 * 60 \ \frac{mm^3}{min} \quad (2.3)$$

Where w_1 and w_2 are weight of the steel samples before (initial) and after (final) machining; t is the machining (logging) time.

III. RESULTS AND DISCUSSION

The experimental data results collected during the experiment while using all the cutting fluids, that is, lard oil cutting fluids (LOCFs), tallow oil cutting fluids (TOCFs), palm oil cutting fluids (POCFs), palm kernel cutting fluids (PKOCFs) and conventional mineral cutting fluids (MCFs) are presented below.

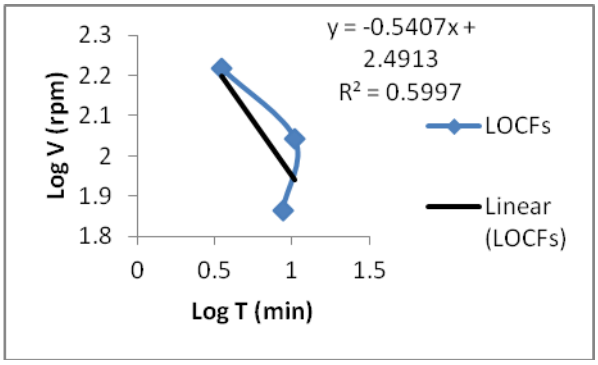

Fig. -8: Natural log-log plot of Cutting Speed against Tool Life for LOCFs

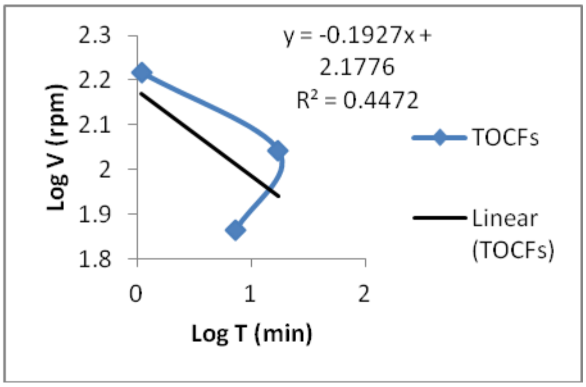

Fig. -9 Natural log-log plot of Cutting Speed against Tool Life for TOCFs

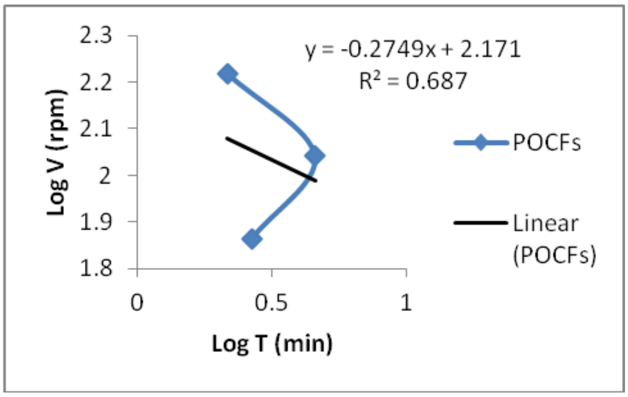

Fig. -10: Natural log-log plot of Cutting Speed against Tool Life for POCFs

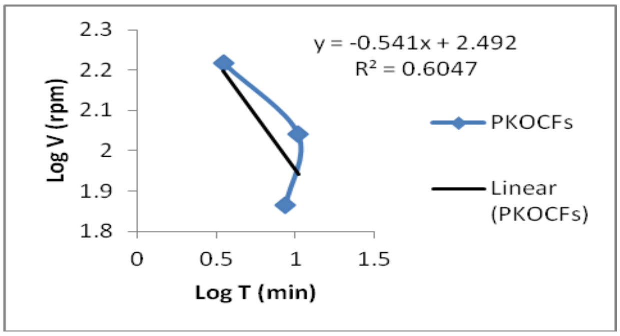

Fig. -11: Natural log-log plot of Cutting Speed against Tool Life for PKOCFs

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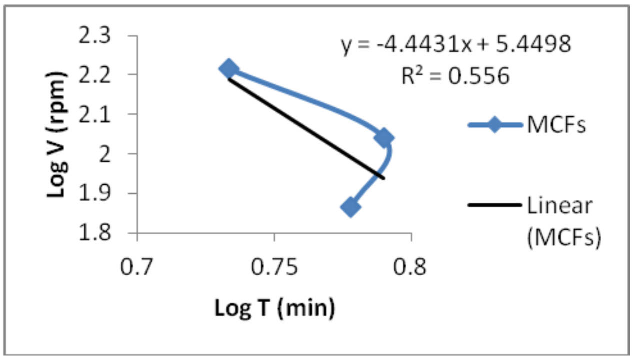

Fig. -12: Natural log-log plot of Cutting Speed against Tool Life for MCFs

Fig. 8- 12 shows the response of cutting speed to tool life using LOCFs, TOCFs, POCFs, PKOCFs and MCFs, respectively. The resulting relationship forms Taylor's tool life (best fit) equation. These also show that the response to tool life using vegetable oils (POCFs and PKOCFs) is higher than in animal oils (LOCFs and TOCFs) and compete favourably with MCFs.

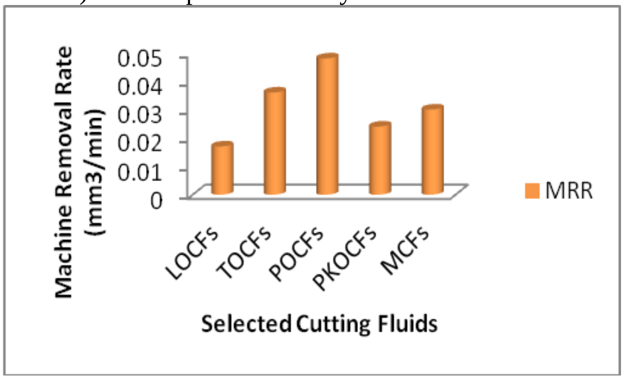

Fig. -13: Plot of MRR against Selected Cutting Fluids

Fig. -13 showed that POCFs produced the most removal rate. That is, more volume of materials was removed per minute using POCFs. The chips thickness formed using POCFs as cutting fluid was highest, probably due to its better lubricating ability, especially at elevated temperature. This allows easier and deeper penetration of cutting tool into workpiece and better material removal rate. This is strictly followed by PKOCs, and then MCFs. LOCFs produced the least removal rate. This is an indication that there was more restriction to the rate of chip formed using LOCFs. This is an evident that LOCFs makes the steel sample less machinable. It could be inferred that PKOCFs are better and could be substituted for MCFs in terms of MRR because lesser chips were formed.

Fig. -14 showed the effect of machining time on the selected cutting fluids under different machining combinations. The plot revealed that POCFs was the fastest. The steel sample was easily machined at the fastest time using POCFs. This is strictly followed by MCFs. The steel sample took longer time of machining completion using TOCFs.

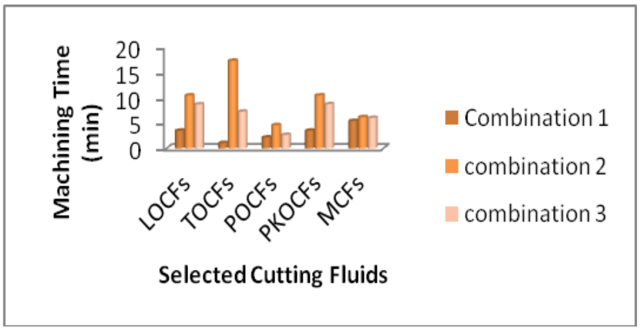

Fig. -14: Plot of Machining Time against Machining Parameters Combination

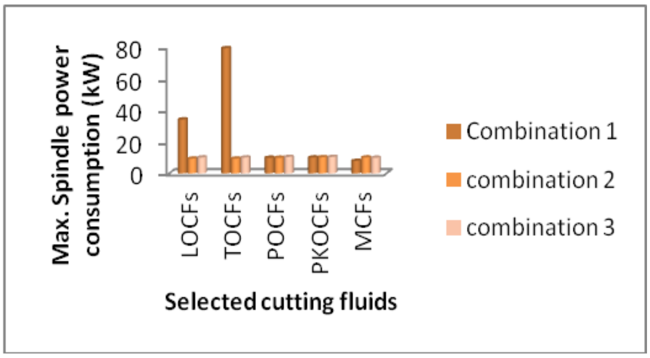

Fig. -15: Plot of Max. Spindle Power Consumption against Selected Cutting Fluids

Fig. -15 showed the plot of Maximum Spindle Power Consumption against Selected Cutting Fluids under different machining parameters combination. The plot revealed that MCFs consumed least spindle power. It could be inferred that POCFs and PKOCFs, as vegetable oil based cutting fluids are the alternative cutting fluid in the absence of MCF. Though POCFs is the best, but the two (POCFs and PKOCFs) consume almost the same spindle power with that of MCFs, while the other two, that is LOCFs and TOCFs as animal oil based cutting fluids consumed most.

Data Logger Results

Fig. -16 Data Logger Showing Spindle Power Consumption at logger time interval under Variable 1 for LOCFs

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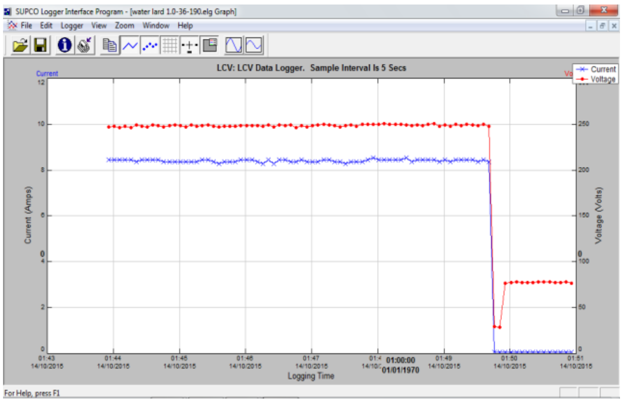

Fig. 3.10: Data Logger Showing Spindle Power Consumption at logger time interval under Variable 2 for LOCFs

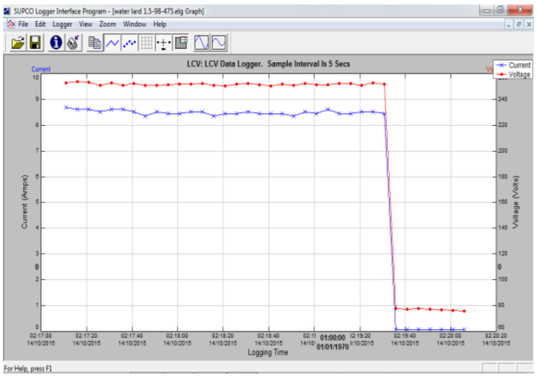

Fig. -17: Data Logger Showing Spindle Power Consumption at logger time interval under Variable 3 for LOCFs

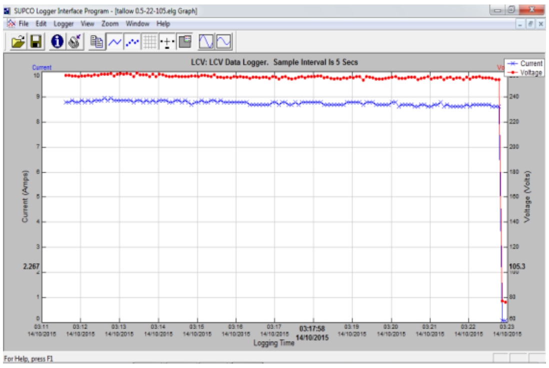

Fig. -18: Data Logger Showing Spindle Power Consumption at logger time interval under Variable 1 for TOCFs

Fig. 16 – 29 shows the data logger results for spindle power consumption at logger time interval under three variables for the selected fluids. The variables were based on the cutting speed (rpm), feed rate (mm/min) and depth of cut (mm). That is (165, 0.22, 1.0), (110, 0.44, 2.0) and (73, 0.11, 3.0) for variable 1, 2 and 3, respectively. The blue line indicated the current (Amps) while the red line represents the voltage (Volts). The data logger results are meant to substantiate results presented in fig 3.8, which revealed that MCFs consumed least spindle power. It could be inferred that POCFs and PKOCFs, as vegetable oil based cutting fluids are the alternative cutting fluid in the absence of MCF because the two consume almost the same spindle power with that of MCFs, while the other two, that is LOCFs and TOCFs as animal oil based cutting fluids consumed most.

In addition, the most consumed spindle power were obtained at variable 3 for all cutting fluids utilized and the least were recorded in variable 1 as a results of the machining parameters combination.

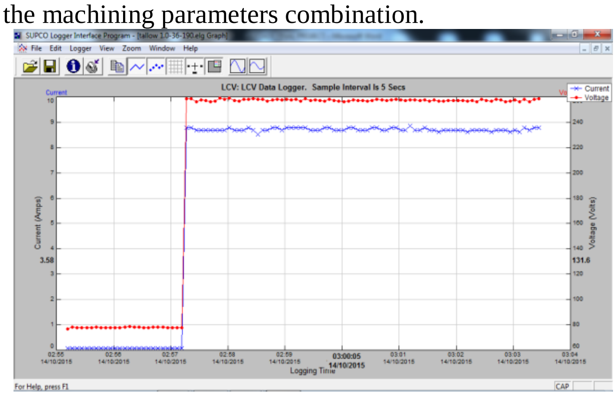

Fig. -19: Data Logger Showing Spindle Power Consumption at logger time interval under Variable 2 for TOCFs

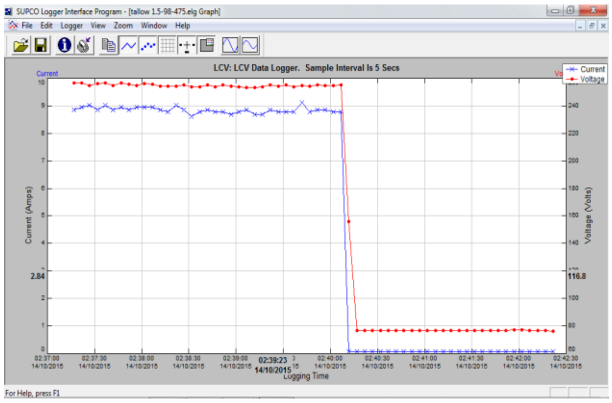

Fig. -20: Data Logger Showing Spindle Power Consumption at logger time interval under Variable 3 for TOCFs

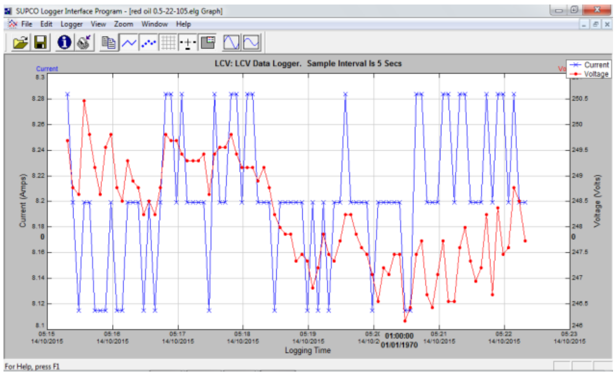

Fig. -21: Data Logger Showing Spindle Power Consumption at logger time interval under Variable 1 for POCFs

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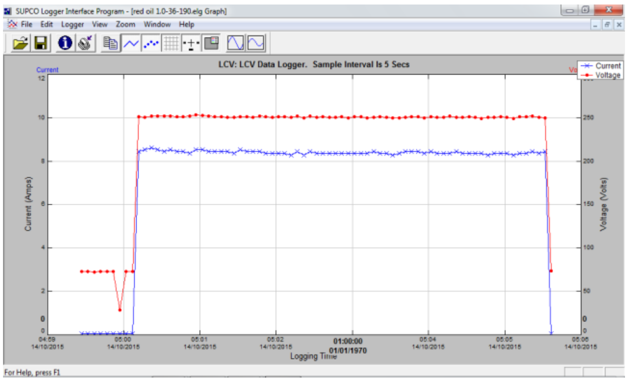

Fig. -22: Data Logger Showing Spindle Power Consumption at logger time interval under Variable 2 for POCFs

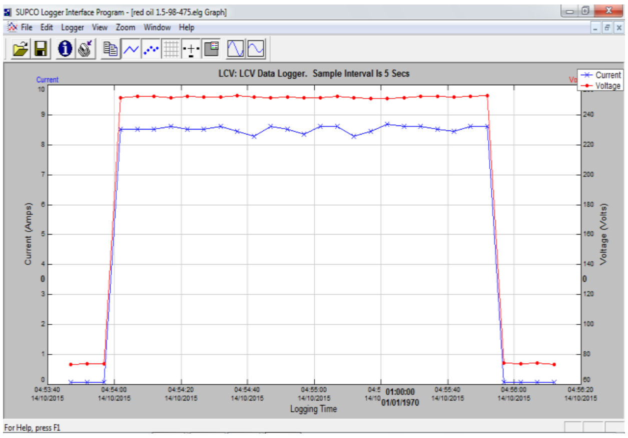

Fig. -23: Data Logger Showing Spindle Power Consumption at logger time interval under Variable 3 for POCFs

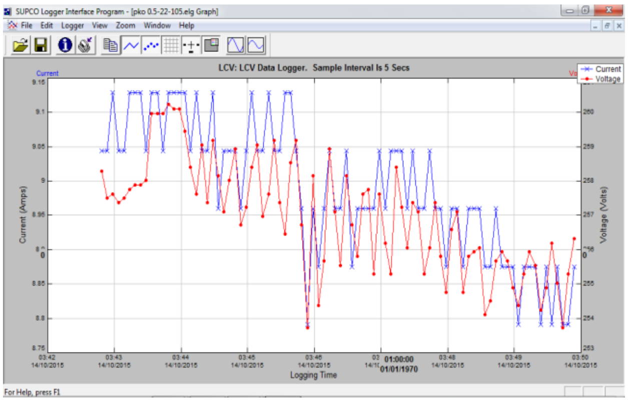

Fig. -24 Data Logger Showing Spindle Power Consumption at logger time interval under Variable 1 for PKOCFs

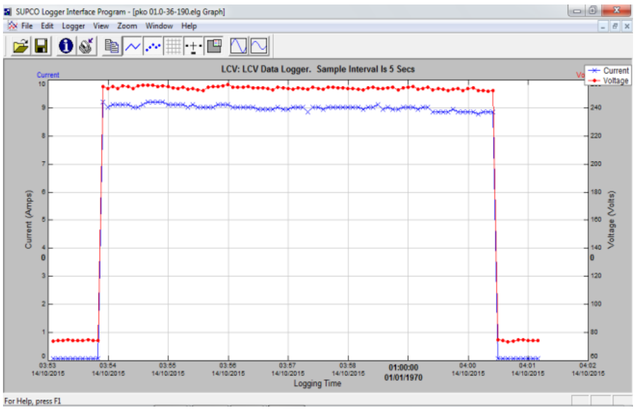

Fig. -25: Data Logger Showing Spindle Power Consumption at logger time interval under Variable 2 for PKOCFs

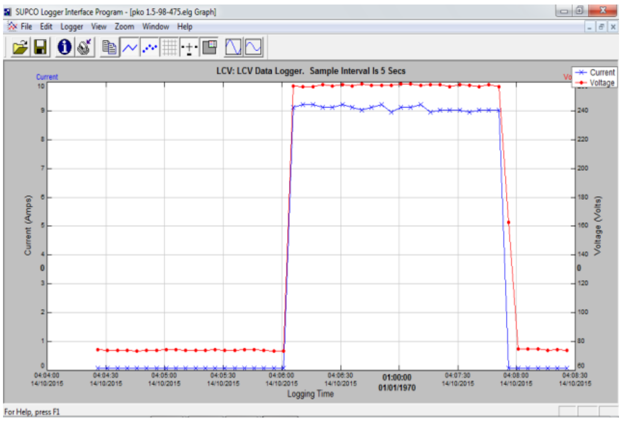

Fig. -26: Data Logger Showing Spindle Power Consumption at logger time interval under Variable 3 for PKOCFs

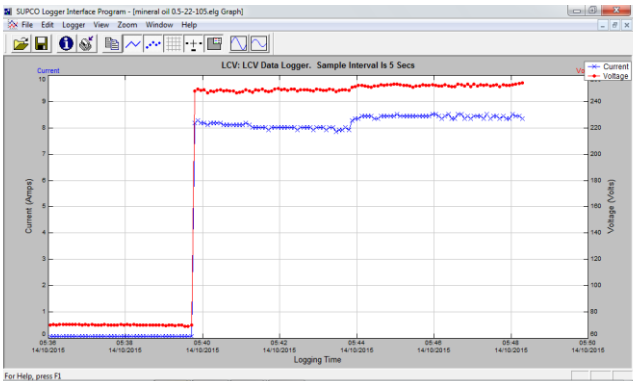

Fig. -27: Data Logger Showing Spindle Power Consumption at logger time interval under Variable 1 for MCFs

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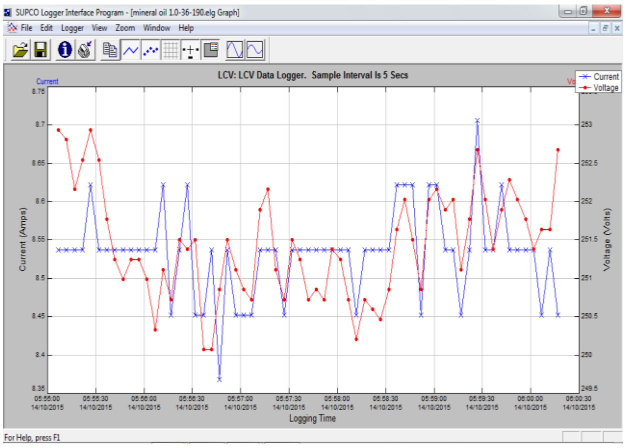

Fig. -28: Data Logger Showing Spindle Power Consumption at logger time interval under Variable 2 for MCFs

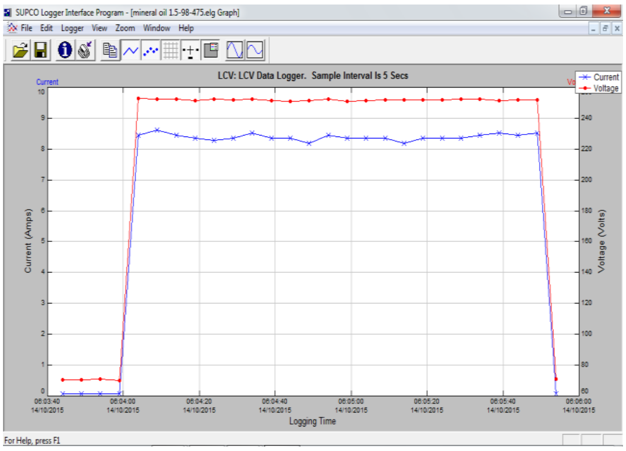

Fig. -29: Data Logger Showing Spindle Power Consumption at logger time interval under Variable 3 for MCFs

IV. CONCLUSION

Cooling and lubrication in machining are important in reducing the severity of the contact processes at the cutting tool-workpiece interface. Historically, water was used mainly as a coolant due to its high thermal capacity and availability [6]. Corrosion of parts and machines and poor lubrication were the drawbacks of such a coolant. It was later discovered that oil added to water (with a suitable emulsifier) gave good lubrication properties with good cooling effects and these became known as the soluble oils, but with environmental challenges to address. Currently, there are wide scale evaluations of the use of metal working fluids (MWFs) in machining, so as to reduce the amount of lubricants in metal removing operations. Mineral oils were also used at this time as these have much higher lubricity, but the lower cooling ability and high costs restricted their use for low cutting speed machining operations.

This study focused on experimental method for investigating the influence of some selected cutting fluids on some selected machining parameters like tool life, spindle power consumption, tool temperature, machine removal rate, and logger time. during the turning of plain carbon steels. Experimental results clearly show that Conventional cutting fluid might be replaced with Non-conventional cutting fluids like POCFs and PKOCFs as they give better performance.

Conclusively, the following salient features were achieved:

1. The introduction of vegetable oil-based metal working fluids in machining applications has made it possible to achieve better performance as reported by all researchers. POCFs showed the best performance at cutting speed (165rpm), depth of cut (1.0mm) and feed rate (0.22mm/min) when compared to mineral oil on turning of plain carbon steels.
2. POCFs are the alternative cutting fluid in the absence of MCF because it consumes almost the same spindle power with that of MCFs. While TOCFs consumed most.
3. When the POCFs and PKOCFs (vegetable based oils) were applied to turning of plain carbon steels, there was remarkable improvement of metal removal rate (MRR), that is, productivity, than when LOCFs and TOCFs were utilized. This substantiates the results obtain in [6] and [3].
4. The cooling property of the selected cutting fluids offers competitive performance with that of conventional mineral-based oil, as shown by the narrow temperature difference between the values obtained.
5. The machining combination, that is, the depth of cut, feed rate and cutting speed had a greater influence on the tool wear.

It has been established that ecology-friendly vegetable-based oils like POCFs and PKOCFs could successfully replace petroleum-based mineral oils as cutting fluids than animal-based oils like LOCFs and TOCFs. With slight modifications and deliberate but careful alterations in some of the components of such oils, even better performing cutting fluids could be obtained.

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