CHAPTER 1

1. Introduction

1.1 Background of study

The tribological improvement characteristics of workpiece-tool-chip system have been achieved in machining process through the application of cutting fluids. Taylor in 1907 reported 40% increment in cutting speed when water coolant was used to machine steel with high speed tools (Taylor, 1907). Improved surface roughness, increased tool life and reduced cutting force were achieved in machining process with the use of cutting fluids (De Chiffre, 1988). The generated heat at the cutting zone can be minimized through the application of cutting fluid either as coolant or lubricant, but only efficient as lubricant at low speed. It equally serves as a chip removal during machining process (Cassin and Boothroyed, 1965). The ineffective of cutting fluids as lubricant at high speed machining is largely due to its inability to penetrate the actual cutting zone between the chip-tool interface at high cutting speed. Conversely, the effect of cooling and lubricating properties of cutting fluid influence each other and this effect decreases with increase in cutting velocity (Kitagawa et al., 1997). Cutting fluids are one of the types of lubricants, which are extensively used in machining processes and there are several types, which may be used to carry out such tasks (Abdalla and Patel, 2006). Therefore, cutting fluid can be defined as any liquid or gas that is applied directly to the machining operation to enhance the machinability. However, most of the cutting fluids are mineral oil based fluids and they increase productivity and the quality of manufacturing operations by cooling and lubricating during metal cutting and forming processes (Julieb et al. 2003). Due to their advantages, the consumption of cutting fluids is increasing in machining industry. It is reported that the European Union alone consumes approximately 320,000 tonnes per year of cutting fluids of which, at least two-thirds need to be disposed (Abdalla et al. 2007). Despite their widespread use, they pose significant health and environmental hazards throughout their life cycle. It is reported that about 80% of all occupational diseases of operators were due to skin contact with cutting fluids (HSE, 1991a; HSE, 1991b; HSE, 1994; HSE, 2000). In the USA alone about seven hundred thousand to one million workers are exposed to cutting fluids (Korde et al. 1993). The compositions of cutting fluids are very complex and may become allergic or irritant sometimes. Water-soluble cutting fluids are sources for microbial toxins which are caused by fungi and bacteria (Zeman et al. 1995), which are more harmful to the operators. To overcome these challenges, various alternatives to petroleum-based cutting fluids are currently being explored by scientists and tribologists. Such alternatives include synthetic lubricants, solid lubricants and vegetable-based lubricants.

The growing demand for biodegradable materials has opened an avenue for using vegetable oils as an alternative to petroleum-based polymeric materials (Bisio and Xanthos, 1995; Li et al. 2001), most especially in machining processes. The public awareness in environmental issues has been growing constantly (Eichenberger, 1991). Lubricants are used in many diverse areas; therefore, their environmental acceptability has become increasingly important. As a result, research on biodegradable functional fluids emerged as one of the top priorities in lubrication in the early 90s which led to a lot of growing number of environmentally friendly fluids and lubricants in the market (Busch and Backe, 1994). Vegetable oils, especially rapeseed (Flider, 1995) and canola (Wessol & Whitacre, 1993) are some of the more promising basestocks for the biodegradable lubricants. They are readily biodegradable and less costly than synthetic basestocks. They often show quite acceptable performance as lubricants (Wessol & Whitacre, 1993).

In general, vegetable oils are highly attractive substitutes for petroleum-based oils because they are environmentally friendly, renewable, less toxic and readily biodegradable (Norrby, 2003; Matthew et al. 2007). Many investigations are in progress to develop new bio-based cutting fluids from various vegetable oils available around the world. Vegetable oils are viable alternative and renewable source of environmentally friendly oils. The majority of vegetable oils consist primarily of triglycerides, which have molecular structure with three long chain fatty acids attached at the hydroxyl groups via ester linkages. The fatty acids in vegetable oil triglycerides are all of similar length, between 14 and 22 carbons long, with varying levels of unsaturation (Asadauskas et al. 1997; Allawzi et al. 1998). Figure 1.1 shows a typical chemical structure of triglyceride of vegetable oil, where R_1, R_2 and R_3 represents the long chains of hydrogen and carbons atoms called fatty acid chains.

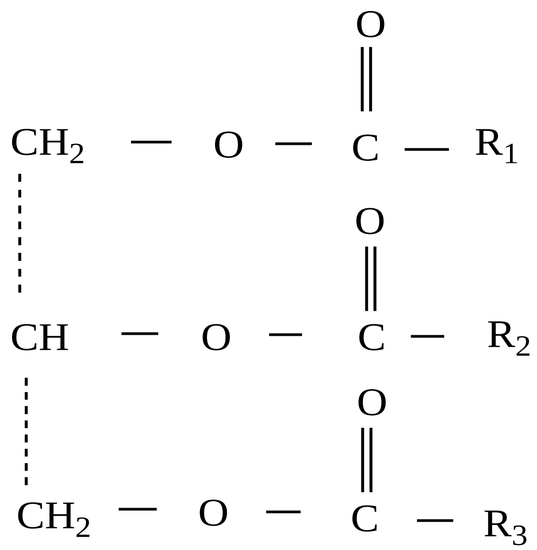

Figure.1.1: Chemical structure of typical vegetable oil
(Source: Van Gerpen et al., Aug, 2002 – Jan, 2004)

The triglyceride structure of vegetable oils provides qualities desirable in a lubricant. Long, polar fatty acid chains provide high strength lubricant films that interact strongly with metallic surfaces, reducing both friction and wear. The strong intermolecular interactions are also resilient to changes in temperature providing a more stable viscosity, or high viscosity coefficient.

The similarity in all vegetable oil structures means that only a narrow range of viscosities are available for their potential use as lubricants. The strong intermolecular interactions whilst providing a durable lubricant film also result in poor low-temperature properties. The fluid also remained biodegradable with low toxicity at all stages of its life. Lubricant formulations are being developed based on the benefits and limitations of vegetable oils. Without additives, vegetable oils out performed mineral base - oils in antiwear and friction (Asadauskas et al. 1997; Asadauskas et al. 1996), scuffing load capacity (Kozma, 1997) and fatigue resistance (Odi-Owei, 1988). Fully formulated vegetable oil lubricants, in comparison to mineral oil counterparts, display a lower coefficient of friction, equivalent scuffing load capacity and better pitting resistance, but also poorer thermal and oxidative stability (Hohn et al. 1999; Arnsek and Vizintin, 1999a; Arnsek and Vizintin, 1999b; Arnsek and Vizintin, 2001; Krzan and Vizintin, 2003a; Krzan and Vizintin, 2003b). Vegetable oils are particularly effective as boundary lubricants as the high polarity of the entire base oil allows strong interactions with the lubricated surfaces. Belluco and De Chiffre (2001) evaluated the performance of a range of mineral and vegetable oil-based cutting fluids in a range of machining operations (turning, drilling, milling and grinding) and vegetable-based oil formulations displayed equal or better performance than the reference commercial mineral oil in all operations. In summary, vegetable oils display many desirable characteristics, which make them very attractive lubricants for many practical applications (Belluco and De Chiffre, 2001, Belluco and De Chiffre, 2004, De Chiffre and Belluco 2002, Xavior and Adithan, 2009). Table 1.1 shows the merits and demerits of vegetable oils as cutting fluids.

Table 1.1: Merits and demerits of vegetable oils as lubricants
(Source: Shashidhara and Jayaram, 2010)

Merit	Demerit
Low production cost	High freezing points
High flash points	Poor corrosion protection
Compatibility with additives	Low thermal stability
High biodegradability	Low oxidative stability
Low toxicity	
Wide production possibilities	
Low pollution of the environment	

The major performance issues such as poor low temperature properties and low resistance to oxidative degradation are addressed by various methods such as (i) reformulation of additives (ii) chemical modification of vegetable based oils and (iii) genetic modification of the oil seed crop (Fox and Stachowiak, 2007; Lou, 1996).

Cutting fluids are normally classified into three main groups viz; (i) neat cutting oils (ii) water – soluble fluids and (iii) gases. The water soluble fluids can be classified as emulsifiable oils (soluble oils), chemical (synthetic) fluids or semi-chemical (semi-synthetic) fluids. Fluids within these classes are available for light, medium and heavy duty performance (El Baradie, 1996). The combination of cooling property of water and lubrication property of oil serve as an advantage when emulsion cutting fluid is used in machining process. This combination can be achieved by preparing cutting fluid concentrate with water and oil and the ratio of water can vary from 92 to 2 depending on the type of machining process. The application characteristics of the three basic chemical formulations of cutting fluids and the classification of water – soluble fluids are shown in Figures 1. 2 and 1.3 respectively.

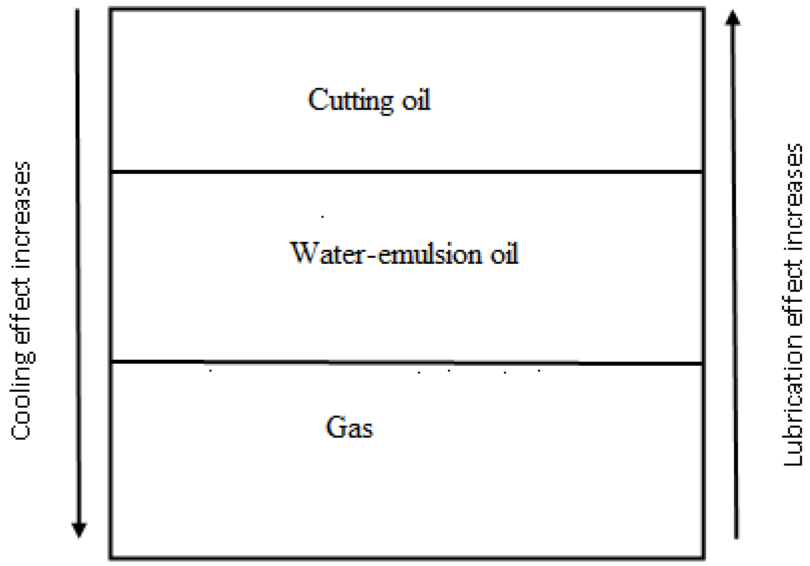

Figure 1.2: Characteristics of application of cutting fluids

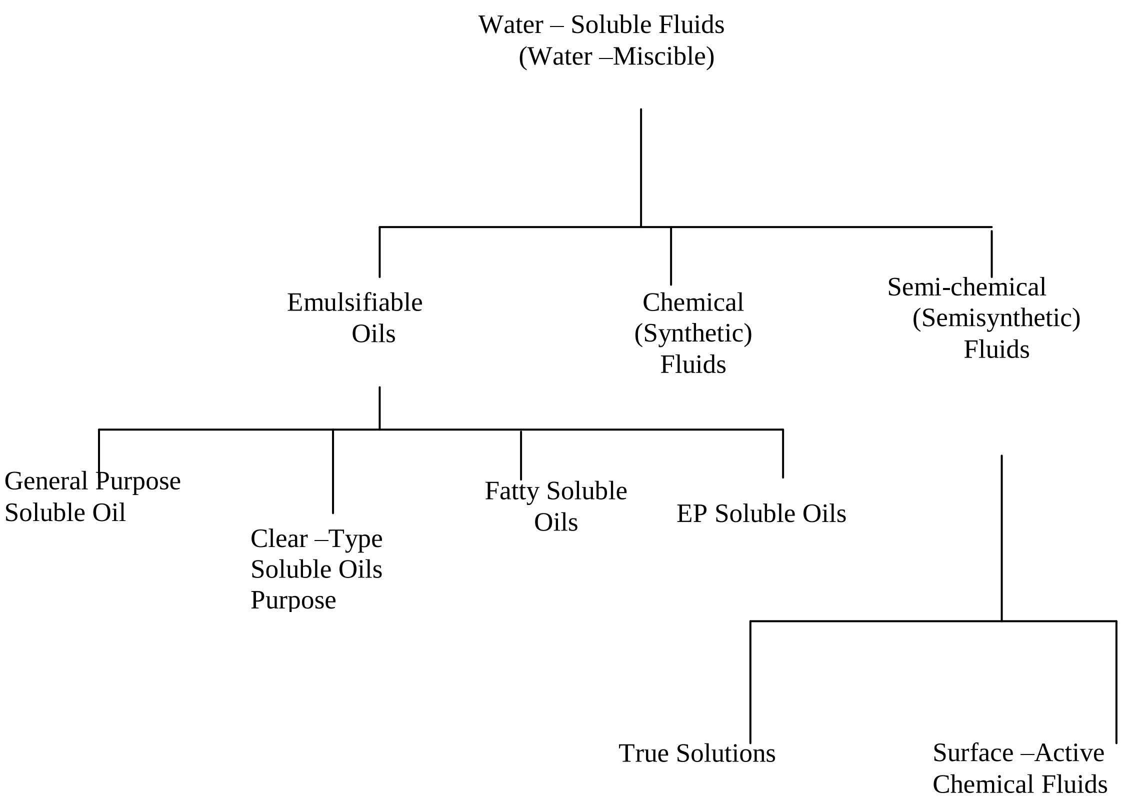

Figure 1.3: Classification of water – soluble fluids
(Source: El Baradie, 1996).

The characteristics of cutting fluid are very complex to meet so many demands, some of these characteristics are lubrication, cooling, no foaming, long life, reduction of dimensional instability, universal application, skin friendly, rust prevention, health and environment friendly etc. The cutting fluids performance in machining process depends on type of tool and workpiece materials through the evaluation of process parameters like flank wear, surface roughness, cutting force and temperature. Hence, the cutting fluid applied in machining processes basically has the following four characteristics (Wisley et al. 2001):

1. To lubricate at low cutting speeds
2. To cool at high cutting speeds
3. To help the chip removal from the cutting zone
4. To protect the machine tool and workpiece against corrosion

In order to reduce the effects of temperature on cutting tools and work material, the application of cutting fluid is necessary. This helps to prolong tool life as a result of less tool wear and improvement in machined workpiece dimensional accuracy (El Baradie, 1996; Avuncan, 1998). Lubrication will make it easier for chip to flow on the rake face of the tool as a result of low friction and when machining materials like aluminum and its alloys, there would be less built-up edge because of the influence of lubricant. This in turn results in better surface finish of the material. Cooling at low cutting speed is not important compared to lubrication in order to reduce friction and avoid built-up-edge formation. In the same vein, cooling is important at high cutting speed, because at high speed, it is difficult for fluid to penetrate the workpiece-tool-interface as lubricant.

1.2 Objectives

The objectives of this study are:

1. To investigate the properties and suitability of vegetable oils as oil-in-water emulsion cutting fluid for machining process.
2. To formulate vegetable oil –in-water emulsion cutting fluid and to evaluate their characteristics.
3. To compare the effect of vegetable oil-in-water emulsion cutting fluids with conventional (mineral based oil) cutting fluid on machining behaviour of AISI 4340 steel material using coated carbide tool.

1.3 Justification of study

Cutting fluids are used as lubrication and processing of materials in industrial sector. About 38 million metric tons of fluids used for lubrication purposes were reported throughout the World in 2005, and this was expected to further increase by 1.2% within a decade (Kline & Company, Inc., 2006). Petroleum-based oils formed about 85% of fluids used as lubricants around the globe (Loredana et al., 2008) and this has caused adverse effects on the environment. The inappropriate application of these petroleum based oils results in environmental problems such as pollution of groundwater, soil contamination and air pollution and consequently, agricultural product and food contamination (Birova et al. 2002). The reduction in the consumption of these types of lubricants was due largely to environmental laws introduced by occupational safety and health administration (OSHA) and other international regulating bodies. This led to the development and utilization of oil from vegetable as cutting fluids (Singh and Gupta, 2006).

Reports have shown that many research groups (Julieb et al. 2003; Joseph, 2007; Jacob et al. 2004; Peter, 2005; Abdalla et al. 2007; Sivasankaran, 1988; De Chiffre and

Belluco, 2002; Belluco and De Chiffre, 2004; Alves and Olivera, 2006; Shashidhara and Jayaram, 2006, Carcel, 2005; Lovell, 2006; Ulf, 2003) have investigated and developed new oils as lubricant for machining process. Companies like Blazer (Swiss), Cargill industrial oils & lubricants (USA) and Renewable lubricants (USA) are at the verge of commercializing vegetable oil as cutting fluid. Because of environmental concerns and growing regulations over contamination and pollution, the increase need for renewable and biodegradable lubricants cannot be over stretched. De Guzman (2002) reported an annual growth rate of 7–10% for environmentally favourable lubricants in US market within a few years as compared to a rate of only 2% for the overall lubricant market. Hence, the need for increased research work in the development of cutting fluids from vegetable oils to bridge the limitation created by mineral oil based cutting fluids is justified.

Machining of materials such as steel alloys results in the formation of high temperature at cutting zone which lead to dimensional inaccuracy and tool failure and consequently affect the surface roughness, as well as chemical degradation of the surface of the workpiece (Dhar et al. 2006, Boothroyd and Knight, 2005; Sharma et al., 2009, Seah et al, 1995). An attempt to mitigate these machining problems of alloys of steel by ensuring effective removal of heat via the introduction of mineral oil based cutting fluid produced significant results compared with dry cutting in term of machining performances (Seah et al., 1995). Unfortunately, it poses another challenge in form of environmental pollution and risk to employee health (Dhar et al., 2006). Moreover, blending of extreme pressure additives with coolants which effectively provide lubrication and cooling at the chip-tool interface equally have health implication because of the presence of chlorine in the chemical composition (Sokovic and Mijanovic, 2001). Nevertheless, it has been established that the application of vegetable oil based cutting fluid reduces cutting temperature and improved tool life depending on workpiece material and method of application (Sharif et al., 2009). Application of vegetable oil based cutting fluid has been widely studied in many machining processes such as in turning process (Avila and Abrao, 2001; Xavior and Adithan, 2009; Krishna,et al., 2010; Ojolo, et al., 2008; Vasu and Reddy, 2011; . Khan et al., 2009); drilling process (Rahim and Sasahara, 2011; Belluco and De Chiffre, 2004; Kuram et al., 2010a); milling process (Kuram et al., 2010b; Sharif, et al., 2009); and grinding process (Alves and Oliveira, 2006 and Herrmann et al., 2007). A search through the available literature as indicated in Table 1.2 reveals that not much has been done, except the work of Avila and Abrao (2001) to develop appropriate vegetable oil based cutting fluid for AISI 4340 steel with a view to improve the machinability of the material.

Table 1.2: List of recent researches in the machining of AISI 4340 steel

S/N	Workpiece Material	Tool Material	Machining Process	Type of cutting fluid	Investigation	Authors
1	AISI 4340 steel	alumina inserts (Al_2O_3 +TiC)	turning process	emulsion without mineral oil, emulsion synthetic, emulsion with mineral oil	tool wear ,tool life, surface roughness and chip formation	Avila & Abrao (2001)
2	AISI 4340 steel	uncoated tungsten	turning process	conventional water soluble lubricant	tool wear	Seah et al., (1995)
3	AISI 4340 steel	ceramics (Al_2O_3 +ZrO_2), CBN (TiC +Al_2O_3)	turning process	dry cutting	surface roughness, tool flank wear and temperature	Cydas (2010)
4	AISI 4340 steel	cemented carbide (TiC/TiCN/Al_2O_3)	turning process	dry cutting	surface roughness, tool wear, cutting force, machine power	Suresh et al., (2012)
5	AISI 4340 steel	coated carbide	turning process	dry, wet (conventional) and MQL	tool wear and surface roughness	Dhar et al., 2006)
6	AISI 4340 steel, AISI 52100 steel, H13 & D2	Cubic boron nitride	turning process	dry cutting	cutting force,	Qian & Hossan, 2007
7	AISI 4340 steel, AISI D2	coated carbide, poly crystalline cubic nitride and alumina cutting tool	turning process	dry cutting	cutting force, surface roughness, tool life and wear mechanism	Lima et al., 2005
8	AISI 4340 steel	cubic boron nitride	turning process	dry cutting	tool life, temperature cutting force	Luo et al., 1999

A critical study of Avila & Abrao, (2001) shows that the role of different types of vegetable oil based cutting fluid on the quality characteristics of machined AISI 4340 steel had not been elucidated. Furthermore, a detail analysis of studies on the machining of AISI 4340 steel shows that they have not been systematically planned to provide a detailed understanding of the factors which affect its machining. Therefore, it is important that the relevant contribution of the factors (tool material, cutting fluid type, feed , cutting speed and depth of cut) controlling the successful machinability of AISI 4340 steel as well as its quality characteristics is understood. As a result, the choice of appropriate machining method and materials (including cutting fluids), parameters that guarantees and excellent machinability of AISI 4340 steel remains a challenge for the research and development engineers in the industry.

In addition, defining the machining method and material parameters to produce surface with low roughness and prolong tool life with the required specifications are both time consuming and require the skill of the manufacturing engineer to develop error free process. Among the few available studies on the machinability of AISI 4340 steel reviewed so far, show that optimizing machining method and material input parameters (includes vegetable based cutting fluid) combinations are most often not considered. Design of Experiment via Taguchi method has been used for various manufacturing processes for the optimization of process parameters (Xavior and Adithan, 2009). Analysis of the outcomes of this cited literature on manufacturing processes reveals that DOE via Taguchi method could be applied to machining of AISI 4340 steel in studying the effect of process and material parameters on the qualities of its machined surface and tool life. Moreover, various mathematical models developed by using this technique are expected to be fairly accurate in predicting the quality characteristics of machined AISI 4340 steel and optimizing the machining and material conditions. However, none of the available literature has addressed the combined effect of influential machining process and materials (including cutting fluid from vegetable oil) parameters on AISI 4340 steel. Since new cutting fluids, materials and machining processes are designed for various applications, it is pertinent that extensive research be carried out for each new cutting fluid, material and machining method for various components manufactured by machining AISI 4340 steel.

Therefore, this study seeks to address this gap in our knowledge of the machining behaviour of AISI 4340 steel by comparing the effect of two different vegetable oil-in-water emulsion cutting fluids with mineral based emulsion cutting fluid on the quality characteristics of AISI 4340 steel during machining. It is expected that the outcome of this investigation will help in understanding why a particular vegetable based cutting fluid may be considered suitable or undesirable for the machining of AISI 4340 steel. Hence, this thesis aims to identify a suitable vegetable-based cutting fluid for AISI 4340 steel among palm kernel and cottonseed oils, with a view to optimizing the properties of the most suitable vegetable based cutting fluid with respect to cutting force, surface roughness, flank wear and studying the types of chip formation justify the reason for the study.

1.4 Scope of study

In this study, selected physico-chemical properties of palm kernel and cottonseed oils were studied. In addition, pH value, viscosity, corrosion level and stability of oil-in-water emulsion cutting fluids formulation were evaluated. The formulation process involved the use of design of experiment (DOE) full factorial method. However, detailed chemical analysis of the oils and the chemical reactions between the oils and the additives are beyond the scope of this study. The study equally assessed the effect of formulated oil-in-water emulsion cutting fluids and compared with conventional (mineral) cutting fluid on the turning behaviour of AISI 4340 steel with coated carbide tool. DOE using Taguchi method was used to analyze the results obtained for cutting force, surface finish and flank wear, while the types of chip formation was equally studied.

1.5 Structure of the thesis

This thesis is structured into five chapters. Chapter one highlights the background, objectives, classification, functions of cutting fluids from vegetable oils. The merits and demerits of vegetable oils with respect to their use as cutting fluid are discussed. A comprehensive literature review on the application of vegetable oil-based cutting fluids in different machining processes is presented in chapter two. Chapter three focusses on the materials used in this study and the methods adopted for cutting fluid formulation from vegetable oils. Methods adopted in determining some selected properties of the two samples vegetable oils used for the research are explained The basic principle of design of experiment (DOE) method using full factorial method used in the formulation of oil-in-water emulsion cutting fluid are highlighted. Similarly, the machining process and the parameters used during the turning of AISI 4340 steel with coated carbide using Taguchi method are explained.

Chapter four discusses the results obtained from all the experiments conducted both during the formulation of vegetable oil-based cutting fluid and its application in the turning of AISI 4340 steel with coated carbide tools with focus on machining output variables such as cutting force, tool life, surface roughness and chip formation types. Analyses of results were done using S/N ratio and ANOVA analysis to study the significant effect of the input parameters on the output parameters. Chapter five consists of the conclusion and recommendation for future work to be carried out to enhance the study of application of vegetable oil-based cutting fluid in machining processes.

CHAPTER 2

2 Literature review

2.1 Vegetable oil-based cutting fluid

This chapter primarily assesses the research in the formulation of cutting fluids from vegetable oils and its application to machining processes. The metalworking fluids (MWFs) industry has provided machinist with alternative choice of several cutting fluids, such as straight mineral oils, combinations of mineral oils and vegetable oils used as cutting oils and 'sud' between 1900 – 1950 (McCoy, 2006). As alloys of steel were developed, machine tool speed increased and as a result of the increment, the stresses incurred in the machining process tended to overwork the cutting fluids. Hence the need for combinations of mineral oils and lard oil or mixtures of free sulphur and mineral oil to address disadvantages of those cutting oils surfaced.

2.1.1 Formulation

The chemical composition and other properties of vegetable oil have allowed it to be used in many products such as food, lubricant and fuels. The chemical nature of fats and oils sourced from vegetable and animal have made it to be of great useful to mankind (Aluyor et al., 2009). Though, records show that animal and vegetable oils were used by early civilizations in various lubrication application, unfortunately, the use of lubricants as metalworking fluids in the metalworking of crafts was not described in those early historical writing (Schey, 1970). No mention of application of metalworking fluids at early stage, but it is a common knowledge that lubricants were used to ease the wire drawing process and it may not be unreasonable to presume that the fluids used then were those that were readily available. These include animal oils and fats (primarily whale, tallow and lard) as well as vegetable oils from various sources such as olive, palm, castor and other seed oils (Dowson, 1979). Schey (1970) observed that metalworking fluid is probably humankind's first technical endeavour and he was amazed that there were no records of their use despite their importance at that early period.

Cutting fluids formulation is an important step toward achieving the best fluid performance and the extension of fluid life by using correct fluid concentration efficiently. Oils and fats are insoluble in water substances that are obtained from vegetable and animal sources. To develop cutting fluid from them require an addition of additives such as emulsifier, antioxidant and anticorrosive agent. Cutting fluid formulated from vegetable and petroleum oils are modified using these additives in order to meet the fundamental requirements. Sulfurization and phosphate modification is one of the several methods used to modify these oil based cutting fluids from vegetable or animal oils (Schwab and Gast, 1970).

Vegetable oils and other fats consist of fatty acids that are most organic solvents and insoluble in water. They can have a wide range of fatty acid profiles such as C18—oleic, linoleic, or lineleic acids. The amount of these fatty acids depends on the vegetable type, the growing season, and the geographical location as a result of the performance of vegetable oil in terms of oxidative stability and pour point depends on these factors. For example, oxidative stability is enhanced with higher oleic acid content and worse pour point (Schwab et al. 1975).

To address these limitation of cutting fluid from vegetable oil, it was recommended or necessary that the chosen additives are not dangerous to both environment and human health. Bartz (2001) listed some substances that were identified as been dangerous to both the health of workers and environment in formulation of cutting fluid, such as: nitrosamines, formaldehyde condensate materials, organic chlorine-containing substances, organic phosphorous-containing substances, polycyclic aromatic hydrocarbons (PAH), such as benzopyrene - PAH and others. He advised that such materials should not be used in the preparation of environmentally friendly cutting fluids.

2.1.2 Composition

Childers (2006) observed that the type of additives used in formulation of cutting fluids contribute to their properties and that these properties are usually mutually exclusive. Table 2.1 shows some additives commonly used in vegetable oils. The main constituents of water miscible fluids are oil, emulsifier, anticorrosion agent, biocide, foam inhibitors to improve stability in hard water. The soluble oils can equally be referred to as emulsion oils or water soluble and sometime comprised of between 60 – 90% oil, with emulsifiers and other additives (Bienkowski, 1993). An emulsifier helps to disperse oil in water when an oil concentrate mixed with water to form cutting fluids (Sluhan, 1994). Emulsifiers also help the oils to cling to the workpiece material during machining process. But sometimes, water-miscible fluids may be in the proportion of 99 to 1% ratio in favour of water, hence the properties of water become an important consideration in fluid formulation (HSE, 2000).

Table 2.1: Additives in vegetable oils (Sharif et al., 2009)

Additives	Function
Zinc diamy dithiocarbamate (ZDDC) Antimony dialkyldithiocarbamate (ADDC)	Anti-wear and antioxidant abilities
Zinc-Dialkyl-Dithio-Phosphate (ZDDP)	Anti-wear / extreme pressure (AW/EP)
S-[2-(acetamido) thiazol-1-yl] dialkyl dithiocarbamates	Anti-wear
Palm oil methyl ester (POME)	Anti-wear
Dibutyl 3.5-di-t-butyl-hydroxy benzylphosphate (DBP)	Anti-wear
Butylated hydroxyl anisole (BHA) Butylated hydroxyl toluene (BHT) Mon-tert-butyl-hydroquinone (TBHQ), propyl gallate (PG)	chain- breaking antioxidants
Zincdithiophosphates (DTP) Dithiocarbamates (DTC)	peroxide decomposers antioxidant

Minerals, gases, organic matter, microorganisms or combination of these impurities in water can make the mixture of oil and water problematic. Hence the properties of water such as hardness and dissolved solids of water quality need monitoring to achieve better fluid performance. The hardness of the water depends on its content of water-soluble calcium and magnesium compounds. The total hardness of water has the greatest effect on the cutting fluids. In hard water, the calcium and magnesium ions react with components of the emulsifying oil. This reaction forms compounds which are not soluble in water and may be precipitated in the circulation system. Since these reactions use up part of the emulsifier, it reduces the stability of the emulsion. This may lead to de-mulsification and oil separation or fluid components segregation. Soft water will increase the risk of foam. Milacron (1996) suggested the ideal hardness of water for making cutting fluids to be between 80 and 125 ppm or drinkable water. The size of droplet produced during formulation process affect the stability of the emulsion. To achieve an average diameter of several micrometers in emulsion formulation, a mechanical or electrical overhead stirrer should be used for mixing the compositions.

2.1.3 Characterization

Alves and de Oliveira (2008) observed that some properties of the formulated fluids, such as;- viscosity, pH value, stability and corrosion level are important properties of oil-in-water. pH value is a good indicator of the condition of cutting fluid. They suggested a pH value of between 9 and 11 for cutting fluids. It has been established that viscosity and pH properties of cutting fluid are important parameters that affect fluid performance during machining process and it maintenance during disposal (Bienkowski, 1993). Hence, whatever pH value adopted for oil-in-water cutting fluids, it would have any of these implications on both worker's health and material as depicted in Fig 2.1.

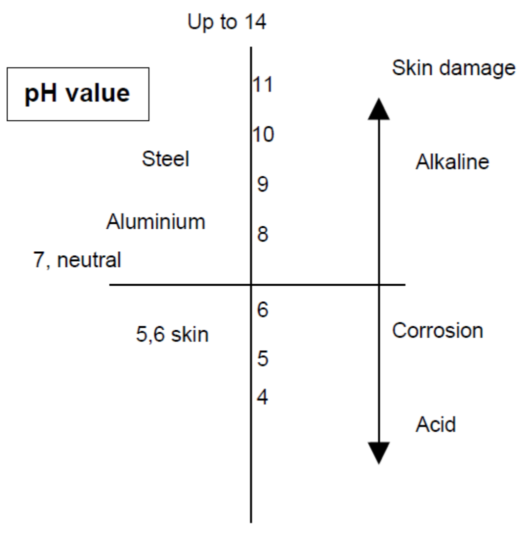

Figure 2.1: Implication of pH value on worker's health and material
(www.theworks-works.com)

(i) if the pH value is too low (acid) the corrosion protection will be reduced as well as the long life stability.

(ii) if the emulsion is to high (alkaline) it will tend to degrease the skin and remove the natural skin protection.

If the pH value of the oil-in-water is low ($pH < 7.0$) the emulsion will be corrosive, hence materials such as steel alloys and aluminum will tend to be corroded under such cutting fluid. On the other hand, high pH value ($pH > 11$) has the tendency to cause skin damage. While, the viscosity of any oil-in-water emulsion depends on oil concentration in the mixture and properties of the oil.

2.1.3.1 Sulfonate castor oil-based cutting fluid

Alves and de Oliveira (2006) developed a new water based grinding fluid formula from sulfonated castor oil to study its environmental requirements on CBN grinding and machining performance. The proposed fluid formulation consisted of the following percentage by volume; 40% of sulfonated castor oil, 35% of water, 5% of derivative of triasine 15% of anticorrosive (synthetic ester) and 5% of emulsifier (polyglycol of synthetic ester. The oil was added first in water and mixed for two minutes and after all additives were added, they were stirred together for fifteen minutes. The emulsion of oil-in-water was stable for 24 hours without reposed, which indicated the stability of the mixture. The properties of the new formulated oil-in-water coolant were investigated and the results are shown in Table 2.2.

Table 2.2: Characterization of new cutting fluid
(Source: Alves and Oliveira, 2006)

Aspect	Oil
Colour	chestnut
Stable solution	yes
pH	10.77
Absolute viscosity	129 cP

The oil-in-water coolant formulated does not have any banned products in its composition and the amounts of bactericide and anticorrosive used are within acceptable values commonly used in commercial products. Biodegradability test was investigated using Ready Biodegradability, 301B CO2 Evolution Test adopted in 1992 (Eisentraeger et al., 2002). The result showed excellent biodegradation as depicted in Figure 2.2.

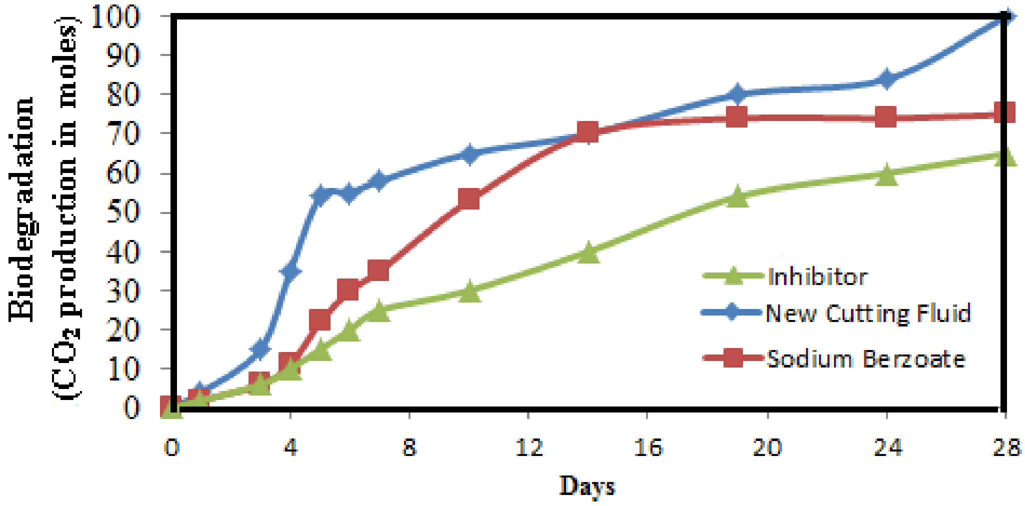

Figure 2.2: Biodegradation test of cutting fluid (Source: Alves and de Oliveira, 2008)

The corrosion test was conducted using few grams of cast iron chips. Chips were placed on disk of filter paper in a Petri dish and humidified in 2 ml of the cutting fluid and then covered. The corrosion level was determined by identifying the number of stained on the filter paper after 2 hours. It was observed that the cutting fluid has ability to inhibit corrosion as shown in Figure 2.3

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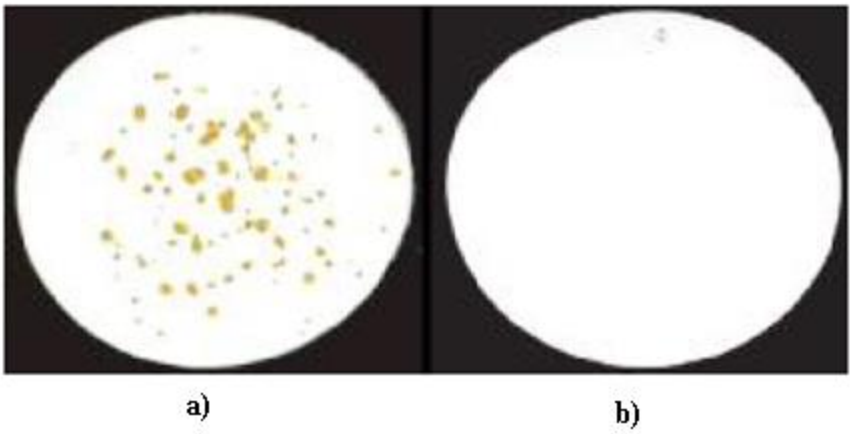


Figure 2.3: Corrosion level (a) before and (b) after the increase in the amount of anticorrosion additive (Source: Alves and de Oliveira, 2008)

2.1.3.2 Crude soybean oil-based cutting fluid

Jacob et al., (2004) studied behaviour of emulsions of different vegetable oils. Crude soybean and modified soybean oils samples were obtained from Volga oil processing Company, Volga, South Dakota and Urethane Soy Systems Inc, Princeton, IL respectively. But the preparation of ozone-modified and sulphur-modified oils was carried out in the laboratory. The emulsion with an average diameter of several micrometers was formulated using a rotation mixer of 2500 rpm for 10 minutes. The stability and phase separation of the emulsion was observed by appearance. It was observed that Nikkol and Eccoterge 200 were stable for all the oils, but emulsion obtained for unmodified oil was stable only for Tween 60. While emulsion obtained with Tween 40 with modified oil was stable moderately and separated after 48 hours. The average droplet size for all the emulsion studied ranged between 7 and 10 µm and none of the emulsion studied showed any rust formation within 24 hours which was consistent with previous finding (Watanabe et al., 1989). Table 2.3 shows the list and summary of the properties of emulsifiers used for preparing oil-in-water emulsions

Table 2.3: Emulsifiers properties (Source: Jacob et al., 2004)

Trade name and class	Emulsifier composition	HLB[a]	Emulsion stability
Tween 40 (non-ionic)	polyoxyethylene (20) sorbitan monopalmitate	15.6	moderately stable for unmodified oil
Tween 60 (non-ionic)	polyoxyethylene (20) sorbitan monostearate	14.9	stable for unmodified oil
Nikkol (non-ionic)	polyoxyethylene (40) sorbitan tetraoleate	11.4	stable for all oils
Eccoterge 200 (non-ionic)	Ethoxylated oleic acid ester	~12.0	stable for all oils

[a]HLB is the hydrophile-lipophile balance of an emulsifier

2.1.3.3 Raw and refined sunflower oil-based cutting fluids

Kuram et al. (2010a) investigated the effects of the cutting fluid types and cutting parameters on surface roughness and thrust force with three different vegetable-based cutting fluids developed from raw and refined sunflower oil and two commercial types (vegetable and mineral based cutting oil) during drilling of AISI 304 austenitic stainless steel with high speed steel E-grade (HSS-E) tool. The oil-in-water emulsion type developed from raw and refined sunflower oil-based contained a mixture of surfactant (Tween 85 and Peg 400, Merck) and different additives in the formula to meet the environmental and health requirements of cutting fluids (Kuram, 2009). The additive concentrations used for the formulation were below 10 % w/w. The characterization of vegetable-based cutting fluids is shown in Table 2.4.

Table 2.4: Characterization of vegetable based cutting fluids
(Source: Kuram et al. 2010a)

MWFs*	pH value (emulsion) 8%)	Density (g/ml)	Viscosity (40 degree C) mm^2/sec		Flash point (^{0}C)	Refractive index
			without additive	emulsion 8%		
CSCF-I	8.70	0.970	71	1.4	218	1.475
SCF-I	9.10	0.980	74	2.0	199	1.474
SCF-II	9.00	0.975	75	1.9	170	1.475
CVCF	9.32	0.960	85	1.5	205	1.476
CMCF	9.40	0.906	29	1.4	175	1.482

*CSCF-I: Crude sunflower cutting fluid; SCF-I: Sunflower cutting fluid; SCF-II: Sunflower cutting fluid (a mixture of two surfactants); CVCF: Commercial vegetable cutting fluid; CMCF: Commercial mineral cutting fluid.

2.2 Applications of vegetable oil-based cutting fluids in machining processes

The machining of certain engineering materials is sometime a difficult task; some of the characteristics that make them difficult 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 such materials. Hence, cutting fluids are normally used to eliminate the effect of heat and friction, provide lubrication between chip tool interfaces and flush away chips from machining of steel alloys and improve surface finish of the work material. Krahenbuhl (2005) reported that vegetable oils-based cutting fluids are viable alternative to petroleum-based metalworking fluids due to the following reasons: (i) vegetable oil possess higher flash point, which give opportunity for reduction in smoke formation and fire hazard during machining process, (ii) vegetable oils provides lubricating film layer, which helps to improve workpieces quality and overall process productivity reducing friction and heat generation.

Krahenbuhl (2002) reported an instance, where vegetable oil technology made it possible to increase production volume by 10 percent, because higher cutting velocity and feed were achieved and also reducing tool cost by 50 percent in producing titanium and stainless steel medical implants. He reported that vegetable oils lubrications made possible a 15 – fold increase in tool life, while tapping steel parts for an automobile application. He concluded that coolants based on vegetable oils have demonstrated an ability to deliver machining performance that in most applications is significantly superior to that of mineral oils and synthetic formulations. The machinability of some ferrous metals using vegetable oil-based cutting fluids is discussed in the subsections below:

2.2.1 Turning process with different workpieces

2.2.1.1 AISI 4340 steel

Avila and Abrao (2001) investigated the performance of three types of cutting fluids (fluid *A* = emulsion without mineral oil; fluid *B* = emulsion synthetic and fluid *C* = emulsion with mineral oil) and dry cutting when continuous turning of hardened AISI 4340 steel (49HRC) using alumina inserts (Al_2O_3 + TiC). They evaluated tool life, surface finish, tool wear mechanisms and chips for both rough and finish machining. The rough machining test was conducted using varying cutting speed (V_c) of 50 to 100 m/min for a feed (*f*) of 0.15 mm/rev and depth of cut (a_p) of 2.0 mm. The finish machining setting was at cutting speed (V_c) of 200 to 400 m/min for a feed of 0.05 mm/rev and depth of cut of 0.5 mm. The tests were conducted according to ISO 3685 standard using a tool life criterion of average flank wear VB_B = 0.3 mm as tests were stopped after 60 min, if criterion had not been met. They observed that during rough turning with feed of 0.15 mm/rev and depth of cut of 2.0 mm, cutting fluid *A* provided the longest tool life, followed by dry cutting and fluid *B* and while worst result was given by the emulsion containing mineral oil (fluid *C*). The same trend was observed when finish turning with feed of 0.05 mm/rev and depth of cut of 0.5 mm, with tool life criterion as VB_B = 0.2 mm. The superior performance of fluid *A* may be attributed to the presence of grease in its composition, which was responsible for improved lubricating action particularly under heavy cutting operations. The effect of reduction in the concentration of fluid *A* from 5 to 3% during finish turning gave the best tool life results. The authors observed that during rough turning at V_c = 50 m/min, f = 0.15 mm/rev and a_p =2.0 m, the lowest surface roughness values were as follows: R_a = 1.7 µm (dry cutting), R_a = 1.73 µm (fluid *A*), R_a = 1.89 µm (fluid B) and R_a = 2.14 µm (fluid *C*). When the cutting speed was increased to 75 and 100 m/min, the best surface finish was obtained with fluid *C*. The reduction of concentration of fluid *A* from 5 to 3% (during the finish turning tests) did not represent any considerable change on surface roughness irrespective of cutting speed and the average surface roughness (R_a) value measured. The authors concluded that the application of a cutting fluid based on an emulsion without mineral oil resulted in longer tool life compared to dry cutting. The reduction in the cutting fluid concentration of emulsion without mineral oil from 5 to 3% resulted in lower tool life, particularly at a cutting speed of 300 m/min.

2.2.1.2 AISI 304 austenitic stainless steel

Xavior and Adithan (2009) also investigated the influence of cutting fluids on tool wear and surface roughness during turning of AISI 304 austenitic stainless steel with carbide tool using three different types of cutting fluids (coconut oil, emulsion and a neat cutting oil- immiscible with water). The experimentation work was based on Taguchi's design of experiment (DOE) with L_{27} $(3)^4$ orthogonal array using cutting speed, depth of cut, feed and types of cutting fluids as critical input parameters. The levels of these parameters are presented in Table 2.5

Table 2.5: Input parameter and their levels (Source: Xavior and Adithan, 2009)

S/ No.	Machining parameters	Unit	Level 1	Level 2	Level 3
1	Feed, *f*	mm/rev	0.2	0.25	0.28
2	Depth of cut, *d*	mm	0.5	1.0	1.2
3	Cutting speed, *Vc*	m/min	38.95	61.35	97.38
4	Type of cutting fluids, D	-	Coconut oil	Soluble oil	Straight cutting oil

Linear regression models were developed to determine the tool wear and surface roughness; while, ANOVA analysis was used to determine the significant parameters that influenced the tool wear and surface roughness. The results obtained shows that coconut oil had greatest influence on the surface roughness and tool wear (1.91, 2.06 and 2.11 µm and 0.045, 0.055, 0.071 mm), followed by straight cutting oil (2.25, 2.50 and 2.43 µm and 0.098, 0.095 and 0.104 mm) and soluble oil had the least effect (2.68, 2.92 and 2.92 µm and 0.076, 0.094 and 0.10 mm) at a constant depth of cut of 0.5 mm, feed of 0.2, 0.25 and 0.28 mm/rev and cutting speed of 38.95, 61.35 and 97.38 m/min. The authors observed that:-

(i) feed had greater influence on surface roughness with 61.54% contribution and cutting speed has greater influence on tool wear with 46.49% contribution for all the cutting fluids.

(ii) the relative performance of the effectiveness of the cutting fluids in reducing the tool wear and improving the surface finish was better when coconut oil was used compared to conventional mineral oil.

2.2.1.3 AISI 1040 steel

Krishna et al. (2010) investigated the performance of nanoboric acid suspensions in SAE-40 and coconut oil during turning of AISI 1040 steel with cemented carbide tool (SNMG 120408). The variation of cutting tool temperatures, average tool flank wear and the surface roughness of the machined surface with cutting speed were studied using nanosolid lubricant suspensions in lubricating oil. The experiments were conducted under the following conditions; cutting speed (60, 80 and 100 m/min); feed (0.14, 0.16, 0.2 mm/rev); depth of cut (1.0 mm). Solid lubricants of boric acid with particle size of 50 nm, lubricating oil SAE-40 and coconut oil with flow rate of 10 ml/min were used for lubrication. The temperature was measured by the embedded thermocouple placed at the bottom of the tool insert in the tool holder. They reported that the cooling action of the lubricant with nanosolid lubricant suspensions was evident from the measurement of the cutting tool temperature. It was observed that cutting temperature increased with cutting speed irrespective of the lubricant and cutting temperature was less with coconut oil compared to SAE-40 for identical cutting conditions. Also, cutting temperature increased with increase in feed at all the lubricant conditions. Tool flank wear was measured at different lubricating conditions and at various cutting speeds. Flank wear increased gradually with increase in speed and feed. The combined effect of solid lubricant and vegetable oil led to the reduction in flank wear with 0.5% nanoboric acid particles suspensions in coconut oil compared to the remaining conditions.

It was reported that surface roughness initially reduced and then increased with increase in cutting speed at all the lubricating conditions and increased with increase in feed. It was equally observed that surface roughness reduced with coconut oil compared to SAE-40 oil and within the coconut oil lubricants, 0.5% nanoboric acid suspensions gave better results. In addition, they concluded that, cutting temperatures, tool flank wear and surface roughness decreased significantly with nano lubricants compared to base oil due to the lubricating action of boric acid and that in all the cases, coconut oil based nano particle suspensions showed better performance compared to SAE-40 based lubricant. This was because of better lubricating properties of the base oil.

2.2.1.4 Mild steel

In another development, Ojolo et al. (2008) experimentally determined the effect of some straight biological oils (groundnut oil, coconut oil, palm kernel oil and shear butter oil) on cutting force during cylindrical turning of three materials (mild steel, copper and aluminum) using tungsten carbide tool. The cutting variables considered during machining process were cutting speed, feed and depth of cut. Spindle speeds of 250, 330, 450 and 550 rpm were used at constant feed of 0.15 mm/rev and 2.0 mm depth of cut for each workpiece. Their results showed that bio-oils were suitable for metalworking fluids, but the effects of the bio-oils on cutting force were material dependent. Groundnut oil exhibited the highest reduction in cutting force when aluminum was turned at a speed of 8.25 m/min and feeds of 0.10, 0.15 and 0.20 mm/rev respectively. Palm kernel oil had the best result when copper was turned at feed lower than 0.15 mm/rev. However, at higher feeds, groundnut oil had the best result for copper. Coconut oil recorded the highest cutting force in all the three materials machined followed by shear butter oil and as such, were very mild in reducing cutting force during cylindrical machining. It was concluded that groundnut and palm kernel oils were effective in reducing cutting force during cylindrical turning of all the three workpieces. Lawal et al. (2007) experimentally agreed with the conclusion of Ojolo et al. (2008) when they studied the performance of cutting fluids developed from four vegetable oils (groundnut oil, palm oil, palm kernel oil and olive oil) and compared with soluble oil and dry cutting in turning of mild steel. The following parameters were used during the machining process; cutting speed (58, 85, 125, 180 and 260 m/min), constant depth of cut (2 mm) and feed (2 mm/rev). Temperature was considered to evaluate the performance of the cutting fluid developed from each of the vegetable oils. As expected the highest temperature of 184.7 ^{o}C was recorded by dry machining at cutting speed of 260 m/min, followed by palm kernel oil

(104.4 ^{o}C), palm oil and olive oil (93.9 ^{o}C) and soluble oil (82.7 ^{o}C). The best performance was recorded by groundnut oil with 71.4 ^{o}C for the same cutting speed.

2.2.1.5 Inconel 600 alloy

Vasu and Reddy (2011), studied the effect of minimum quantity lubrication with Al_2O_3 nanoparticles on surface roughness, tool wear and temperature dissipation in machining Inconel 600 alloy. The Taguchi approach was based on Taguchi's L_9 orthogonal array as employed with various combination of input levels of parameters and the machining conditions are shown in Tables 2.6.

Table 2.6: Experimental Specifications (Vasu and Reddy, 2011),

Machine tool	precision engine lathe, capacity 4.5V
Work piece	Inconel 600 (dia. 20 mm)
Cutting tool	coated carbide inserts
Insert code system	CNMG1 20408 –HF
Cutting velocity, Vc	40, 50 and 60 m/min
Feed, f	0.08, 0.12 and 0.16 mm/rev
Depth of cut	0.4, 0.8 and 1.2 mm
MQL supply	air: 5 bar, lubricant: 100 ml/h
Vegetable oil	Coolube 2210 ^{EP}
nanoparticles	Al_2O_3
environment	dry, MQL and MQL with nanofluid (4% volume fraction of Al_2O_3 and 6% volume fraction of Al_2O_3

The study showed a reduction of surface roughness in the MQL + 6% Al_2O_3 nanofluid condition as compared to dry, MQL and MQL +4% Al_2O_3 nanofluids. This was attributed to the stresses at tool-chip interface and temperature intensive in the dry cutting condition. It was observed that plain MQL condition gave a better surface finish than the dry cutting process, depending on the control of the auxiliary cutting edge of abrasion, chipping and built-up edge formation as a result of deterioration. It was equally observed that MQL with 6% Al_2O_3 nanofluid further exhibited better thermal properties such as heat transfer coefficients and higher thermal conductivity compared with the plain MQL. There was a reduction of tool tip interface temperatures in MQL +6% Al_2O_3 nanofluid condition as compared to dry, MQL and MQL + 4% Al_2O_3 nanofluid. It was observed that MQL + 6% Al_2O_3 nanofluid enabled a reduction of the average tool tip interface temperature by about 12 to 20 per cent, depending on process parameters' levels.

There was a reduction of cutting forces in MQL + 6% Al_2O_3 nanofluid conditions as compared to other conditions at all the experimental combinations. This was because of cutting zone temperature reduction, which resulted in less friction and a decrease in the formation of built-up edges. A reduction of 30 to 35% of cutting forces was observed when MQL + 6% Al_2O_3 nanofluid was applied. In MQL + Al_2O_3 nanofluid machining conditions, nanofluid helped to reduce the temperature, resulting in a decrease of built-up edge formation because of the enhanced thermo physical properties of nanofluid. The tool life increased by 45 per cent with MQL + 6% Al_2O_3 nanofluid as coolant than dry cutting. Chips obtained in machining Inconel 600 at different environment proved that in minimum quantity lubrication, there is an appreciable changes in chip formation. But chips in MQL with Al_2O_3 nanofluid do not change appreciably than plain MQL condition, but the continuity was decreased and the colour of the chips becomes much lighter, i.e. metallic from brown. This confirmed that the temperature and cutting forces were reduced while machining with MQL with different volume concentrations of Al_2O_3 nanoparticles.

2.2.1.6 AISI 9310 steel

Similarly, Khan et al. (2009) studied the effects of minimum quality lubrication (MQL) using vegetable oil based cutting fluid on turning performance of AISI 9310 low alloy steel with uncoated carbide tool and compared with completely dry and wet machining in terms of chip-tool interface temperature, chip formation mode, tool wear and surface roughness. The process parameters used were cutting velocity (223, 246, 348 and 483 m/min), feed (0.10, 0.13, 0.16 and 0.18 mm/rev) and depth of cut (1.0 mm). The average chip-tool interface temperature was measured using the tool-work thermocouple technique and plotted against cutting velocity for different feeds and environments undertaken. They showed that, with the increase in cutting velocity and feed, average chip-tool interface temperature increased. They found that the form (shape and colour) and thickness of the chips directly or indirectly indicated the nature of chip-tool interaction influenced by the machining environment. This depend on the mechanical properties of the work material, tool geometry particularly the rakes angle, levels of cutting velocity and feed, nature of chip-tool interaction and cutting environment.

They found that when machining with MQL, the form of these ductile chips did not change appreciably, but their back surface appeared much brighter and smoother. The colour of the chips became much lighter i.e. blue or golden from burnt blue depending on cutting velocity and feed, due to reduction in cutting temperature by MQL. The gradual growth of average principal flank wear, the predominant parameter to ascertain the expiry of tool life were observed under all the environments and it indicated steady machining without any premature tool failure by chipping, fracturing etc., establishing proper choice of domain of process parameters. The variation in surface roughness observed during turning AISI 9310 low alloy steel by uncoated carbide tool at a particular set of cutting velocity, feed and depth of cut under dry, wet and MQL conditions. As MQL reduced average auxiliary flank wear and produced no notch wear on auxiliary cutting edge, surface roughness increased very slowly under MQL conditions. However, the surface roughness deteriorated drastically under wet machining compared to dry, which might possibly be attributed to electrochemical interaction between tool and workpiece. MQL appeared to be effective in reducing surface roughness.

2.2.2 Drilling process with different workpieces

2.2.2.1 Titanium alloys

Rahim and Sasahara (2011) equally studied the potency of minimum quantity lubricant palm oil (MQLPO) and minimum quantity lubricant synthetic ester (MQLSE) during drilling of titanium alloys with coated carbide drill inserts. The holes were drilled under the action of the external air blow, minimum quantity lubricant (MQL) and flood coolant conditions (water soluble type). The first stage of the experiment involved the use of cutting speed of 60, 80 and 100 m/min, feeds of 0.1 and 0.2 mm/rev. Thrust force, torque and workpiece temperature were measured and compared. The second stage of the experiment involved drilling of hole of a depth of 10 mm at the constant cutting speed of 60 m/min, feed of 0.1 mm/rev and the following tool life criteria (i) average flank wear, *VB*(av) = 0.2 mm, (ii) maximum flank wear, *VB(*max) = 0.3 mm, (iii) corner wear = 0.3 mm, (iv) chipping = 0.2 mm, (v) catastrophic failure and (vi) cutting distance = 440 mm (due to the shortage of workpiece material) to evaluate the tool life performance. The flood condition had the lowest torque among the other conditions tested. The air blow did not reduce the drilling torque as much as the other coolant-lubricant conditions as it recorded the highest torque value of 14.4 Nm. The thrust force and torque for the air blow condition were the highest followed by MQLSE, MQLPO and flood cutting conditions.

The effect of various cutting speeds and feeds on MQL conditions showed that thrust force and torque decreased with an increase in the cutting speed. MQLSE and MQLPO recorded the lowest thrust force of 2318 N and 1954 N at the cutting speed of 100 m/min and feed of 0.1 mm/rev, which translated into a reduction of 27% and 19% for MQLSE and MQLPO respectively. The torque for MQLSE at cutting speed of 100 m/min reduced to 9.6 and 13.7 Nm at a feed of 0.1 and 0.2 mm/rev respectively.

MQLPO induced the lowest torque at the cutting speed of `100 m/min and feed of 0.1 mm/rev, which indicated a 32% reduction when the cutting speed increased from 60 to 100 m/min. The workpiece temperature was measured at two locations. The air blow cutting condition recorded the maximum workpiece temperature at both locations. MQLSE cutting condition had lower temperature than the air blow cutting condition with a reduction of 15% and 6.5% respectively at the two locations. MQLPO condition at the two locations recorded the lowest temperature in comparison to the MQLSE and air blow cutting conditions.

The second experimental set up showed that, the flank wear rapidly grew and suffered from excessive chipping. A significant reduction in tool life for a drilling time of 48 s or 110 mm for the air blow conditions was recorded. The flank and corner wear rate was gradual and grew progressively for MQLSE and MQLPO. MQLPO condition produced lower tool wear rate in comparison to MQLSE condition. The flood condition also showed superior performance by having the lowest flank wear and corner wear in comparison to air blow conditions. MQLPO exhibited the lowest tool wear rate than the MQLSE and air blow conditions compared to flood condition. An increment of 554 % in tool life was achieved by MQLPO, MQLSE and flood conditions compared to the air blow condition at the cutting speed of 60 m/min and feed of 0.1 mm/rev.

2.2.2.2 AISI 316 austenitic stainless steel

Belluco and De Chiffre (2004) have studied the performance of vegetable-based oils in drilling AISI 316L austenitic stainless steel using conventional 'High Speed Steel' Coated (HSS-Co) tools. The efficiencies of six cutting oils were evaluated by measuring tool life, cutting forces and chip formation. They used commercial mineral-based oil as reference product and five vegetable-based (rapeseed oil) cutting fluids at different levels of additives for the experiment shown in Table 2.7.   Analysis of variance

(ANOVA) was performed to investigate the effect of different fluids on all measured parameters (Montgomery, 1997).

Table 2.7: Basic characteristics of cutting fluids (Source: Belluco and De Chiffre, 2004)

Name	Type	Description	S-add	P-add
RM (ref oil)	commercial oil	mineral oil-based, general purpose, 20 cSt at 40 ^oC	-	-
RV	commercial oil	vegetable oil-based, general purpose, 19 cSt at 40 ^oC	-	-
A	Formulated oil	Blend of rapeseed oil and ester oil, general purpose, 20 cSt at 40 ^oC	++	++
B	Formulated oil	Blend of rapeseed oil, ester oil and meadowfoam oil, general purpose, 20 cSt at 40 ^oC	++	++
C	Formulated oil	Blend of rapeseed oil and ester oil, mild duty, 20 cSt at 40 ^oC	+	+
D	Formulated oil	Blend of rapeseed oil, ester oil and meadowfoam oil, mild duty, 20 cSt at 40 ^oC	+	+

S-add and P-add columns represent amount of sulphur and phosphor containing additives, at the levels low (+), middle (++) and not available (-)

The thrust force was significant for both the whole life span of the tool and the measurements were performed at the beginning of the tool life span. They concluded that there was relative increase in tool life of 177% with the best fluid, whereas the decrease of cutting thrust force was less than 7%. All vegetable-based fluids performed better than the commercial mineral oil used as reference product.

2.2.2.3 AISI 304 austenitic stainless steel

Kuram et al. (2010a) also studied the effect of cutting fluid types and cutting parameters on surface roughness and thrust force with three different vegetable-based cutting fluids developed from raw and refined sunflower oil and two commercial types (vegetable and mineral based cutting oils) during drilling of AISI 304 austenitic stainless steel with high speed steel E-grade (HSS-E) tool. The vegetable oil based cutting fluids were formulated with various additives to meet the specifications such as resistance to bacterial growth, corrosion, antifoaming agent and antiwear characteristics (Kuram, 2009). Table 2.8 shows the characteristics of vegetable - based cutting fluids developed for the study.

Table 2.8: Characteristics of vegetable based cutting fluids (Source: Kuram et al. 2010)

MWFs*	pH value (emulsion 8%)	Density (g/ml)	Viscosity (40 ^oC) mm^2/sec		Flash point (^0C)	Refractive index
			without additive	emulsion 8%		
CSCF-I	8.70	0.970	71	1.4	218	1.475
SCF-I	9.10	0.980	74	2.0	199	1.474
SCF-II	9.00	0.975	75	1.9	170	1.475
CVCF	9.32	0.960	85	1.5	205	1.476
CMCF	9.40	0.906	29	1.4	175	1.482

*CSCF-I: Crude sunflower cutting fluid; SCF-I: Sunflower cutting fluid; SCF-II: Sunflower cutting fluid (a mixture of two surfactants); CVCF: Commercial vegetable cutting fluid; CMCF: Commercial mineral cutting fluid.

They considered spindle speed, feed and drilling depth as input parameters with two sets of experimental design. In the first set of experimental design, they studied the effect of spindle speeds (520, 620 and 720 rpm) at a constant feed of 0.12 mm/rev and depth of 21mm. while in the second set, they studied the effect of feeds (0.08, 0.12, 0.16 mm/rev) at a constant spindle speed of 620 rpm and drilling depth of 21 mm. From the analysis, the following observations were made:-

(i) an increase in the spindle speed and change of cutting fluid type decreased the thrust force at the feed of 0.12 mm/rev and drilling depth of 21 mm, which was consistent with literature (Davim et al. 2006; Basavarajappa et al. 2008; Ramulu et al. 2008);

(ii) with sunflower cutting fluid (SCF-I), the thrust force was lower and it was minimum when the spindle speed was 720 rpm.

(iii), when the spindle speed was 620 rpm, and drilling depth was 21 mm, the thrust force decreased as the feed decreased and this was consistent with previous findings (Basavarajappa et al. 2008; Mendes et al. 2006; Shetty et al. 2006);

(iii) at a feed of 0.12 mm/rev and drilling depth of 21 mm, an increase in spindle speed improved surface finish and this was in agreement with findings from other researchers (Davim et al. 2006; Basavarajappa et al. 2008; Rivero et al. 2006; Tsao, 2007).

However, the minimum surface roughness was achieved at spindle speed of 720 rpm with commercial vegetable cutting fluid (CVCF) as lubricant. SCF –I was found to be the most effective in reducing surface roughness as spindle speed increased. It was observed that by increasing the spindle speed from 520 rpm to 720 rpm, the surface roughness decreased by up to 32% for SCF –I. Sunflower cutting fluid – a mixture of two surfactants (SCF-II) and CVCF resulted in lower surface roughness at feed of 0.08 mm/rev. SCF –II lubricant resulted in minimum surface roughness at feeds lower than 0.12 mm/rev.

2.2.3 Milling process with different workpieces

2.2.3.1 AISI 304 austenitic stainless steel

Kuram et al. (2010b) performed extensive research on two different vegetable oil-based cutting fluids developed from refined canola and sunflower oils and a commercial type semi–synthetic cutting fluid to determine the optimum conditions for tool wear and forces during milling of AISI 304 austenitic stainless steel with carbide tool material (Iscar HM90 APKT 100304PDR IC 908). Cutting speed, feed, depth of cut and types of cutting fluids were considered as input machining parameters using Taguchi L_9 (3^4) orthogonal array experimental plan. Table 2.9 shows the characterization of vegetable oil-based cutting fluids used for the research.

Table 2.9: Characterization of vegetable based cutting fluids for milling process (Source: Kuram et al. 2010b)

MWFs*	pH value (emulsion 8%)	Density (g/ml)	Viscosity (40 ^oC) mm^2/sec		Flash point (^0C)	Refractive index
			without additive	emulsion 8%		
SCF-II (8% EP)	8.92	0.96	91	4.1	217	1.4775
CCF–II (8%EP)	9.00	0.97	110	3.9	232	1.4770
CSSF	9.18	0.98	75	1.7	235	1.4825

- SCF-II (8%EP): sunflower cutting fluid with 8% EP additive; CCF-II (8%EP): canola cutting fluid with 8% EP additives; CSSF: commercial semi- synthetic cutting fluid

Mathematical models for cutting parameters and cutting fluids were obtained from regression analyses to predict tool wear and forces. S/N ratio and ANOVA analyses were also performed to identify the significant parameters influencing tool wear and forces. The tool wear and force model equations developed in the study are shown in equations 2.1 – 2.3.

The tool wear model equation is given below

$$VB = 0.216 - 0.00618 * V - 0.33 * f + 4.42 * a_p + 0.0598 * CF \quad (2.1)$$

The force model equations are given below

$$F_X = -110 + 0.113 * V + 210 * f + 877 * a_p - 0.2 * CF \quad (2.2)$$

$$F_Y = -75 + 0.007 * V + 83 * f + 843 * a_p + 1.0CF \quad (2.3)$$

where V_B = tool wear in mm, V = cutting speed in m/min, f = feed in mm/rev, a_p = depth of cut in mm and CF = cutting fluid, where the numerical values for CF are 1, 2, and 3 for SCF-II, CCF-II and CSSF respectively as shown in Table 2.10.

Table 2.10: Machining inputs and their levels (Source: Kuram et al. 2010)

Level	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Cutting fluids
1	150	0.20	0.2	SCF-II
2	175	0.25	0.3	CCF-II
3	200	0.30	0.4	CSSF

The multiple linear regression analysis used for the modeling agreed with the result obtained for tool wear, which were between the range of 0.010 and 0.980 mm for cutting speed (150, 175 and 200 m/min); feed (0.20, 0.25 and 0.30 mm/rev); depth of cut (0.2, 0.3 and 0.4mm) for various cutting fluids used. The S/N ratio analysis to determine the optimal machining conditions for various cutting fluids were investigated as follows:-

(i) the tool wear was investigated at 200 m/min cutting speed, 0.30 mm/rev feed, 0.2 mm depth of cut for sunflower cutting fluid with 8% extreme pressure additive (SCF –II, 8%EP).

(ii) the horizontal cutting force was investigated at 150 m/min cutting speed, 0.20 mm/rev feed, 0.2 mm depth of cut for canola cutting fluid with 8% extreme pressure additives (CCF-II, 8% EP).

(iii) the vertical force was investigated at 150 m/min cutting speed, 0.20 mm/rev feed, 0.2 mm depth of cut and SCF - II (8%EP).

The depth of cut was found to have a greater influence on the tool wear and force components. The ANOVA analysis was conducted at 95% confidence level.

2.2.3.2 AISI 420 stainless steel

Sharif et al. (2009) evaluated the feasibility of using palm oil based cutting lubricant through the use of minimum quantity lubricant (MQL) method during end milling of hardened stainless steel (AISI 420) with coated carbide tool materials (TiA1N and A1TiN). Cutting forces, tool life and surface roughness were evaluated under the following machining conditions, cutting speed (100, 130 and 160 m/min), feed (0.05 mm/tooth), axial depth of cut (12 mm), radial depth of cut (1 mm). The cutting fluids used were fatty alcohol, palm olein, palm olein with additive A and palm olein with additive B.

From the cutting test, tool wear progression was gradual for palm oil and fatty alcohol, while for the dry and flood cutting, the tool wear progressed rapidly. Initial rates of tool wear for palm oil and fatty alcohol showed similar trend and increased drastically after the average wear reaching 0.1 mm wear land. Three distinct stages of wear were observed namely, the (i) primary wear, (ii) normal (secondary) wear, and (iii) sharp (tertiary) wear. The rate of wear was high with dry cutting and cutting with flooded coolant. However, with palm oil and fatty alcohol coolant, the rate of wear was rather low. The highest tool life achieved was 160.3 minutes for palm oil lubricant, followed by 137.7 minutes for fatty alcohol, 39.8 minutes for flood cutting and 35.2 minutes for dry cutting. The surface roughness for palm oil and fatty alcohol were 0.73 µm and 0.69 µm at initial stage and finally improved to 0.31 µm and 0.48 µm respectively. While for dry and flood coolant conditions, the surface roughness were 0.24 µm and 0.29 µm at initial stage and finally increased to 0.54 µm and 0.72 µm respectively.

2.2.4 Grinding process with different workpieces

2.2.4.1 Mild steel (SAE 1020)

Alves and Oliveira (2006) studied the mechanical performance and environmental impact of a new cutting fluid developed for grinding process using cubic boron nitride (CBN) tool on SAE 1020 mild steel. Two types of fluids (cutting oil and a semi-synthetic fluid) along with formulated cutting fluid were tested to compare the performance. The parameters evaluated were radial wheel wear, and workpiece roughness. The grinding conditions applied in the experiments were cutting speed (V_s) = 33 m/s, workpiece speed (V_f) = 11.5 mm/s, grinding width (b) = 6.5 mm, grinding wheel penetration (a) = 25 μm, the peripheral disk dresser velocity (V_r) = 38 m/s and dressing depth of cut (a_d) = 10 µm. Successive dressing strokes of 10 µm in diameter were performed until uniform profile was obtained.

The study showed that when semi-synthetic cutting fluid with higher cooling ability and lower lubricant properties was used, a higher wheel wear of approximately 8 µm in radius was achieved. The concentration of 21% of the new formulated fluid showed similar performance with high value of grinding ratio. At high concentration of 32%, the new cutting fluid was not good, because chips agglomeration was observed, which increased the friction between workpiece and wheel leading to increase wheel wear.

They reported high roughness values for the two cutting fluids with high viscosity (cutting oil and the new cutting fluid), which was attributed to chips agglomeration. At low concentration of 15 and 21%, the new cutting fluid caused a decrease in the roughness value and the best performance was observed when a concentration of 21% of the new cutting fluid had a roughness value lower than 0.60 µm. The new cutting fluid at 32% and the cutting oil presented a similar behaviour as there were increases in the roughness values (ranges around 0.90 µm) as well as in the volume of material removal. The semi-synthetic fluid presented good results with roughness around 0.60 µm. The study investigated the biodegradability of the new cutting fluid using the 'Ready Biodegradability' test and concluded that the cutting fluid was environmentally friendly.

2.2.4.2 Hardened bearing steel (100Cr6, 62HRC)

Herrmann *et al.*, (2007) equally investigated the technical, ecological and cost assessment from a life cycle perspective of coolants made of native ester. The research involved carrying out technical tests of different coolants including screening of relevant physical properties and grinding tests on pilot station and on industry scale using hardened bearing steel (100Cr6, 62 HRC) workpiece material and CBN grinding wheel. The grinding process parameters used were; cutting speed (V_c) = 60 m/s, wheel diameter (d_s) = 40 mm, width of cut (a_p) = 10 mm, workpiece diameter (d_w) = 110 mm and specific material removal rate (Q'_w) = 2 mm^3/(mm*s). Technical assessment, life cycle assessment and life cycle costing were considered to evaluate the performance of cutting fluids.

The flash point and viscosity of the developed esters were observed to meet the general requirements of cutting fluids. Grinding forces obtained indicated that a stable grinding process was possible with all the tested ester oils. It was observed that the tendency to lower the cutting force as long as the test lasted was caused by sharpening grinding wheel topography, but not by the change from one ester oil to another. The quality of workpiece surface was reported not to be influenced negatively by the developed native coolant as the measured values fluctuated in a normal range for a grinding process under the chosen conditions. The mass and energy fluxes throughout the life cycles of five coolants were compared using the life cycle analysis (LCA) methodology according to ISO 14040 family (Dettmer, 2006). A system output of 1,000 workpieces processed with the respective lubricant to determine the environmental burdens was employed. The used cooking oil product followed by the animal fat product caused the lowest potential impact on the environment as shown in Fig 2.4

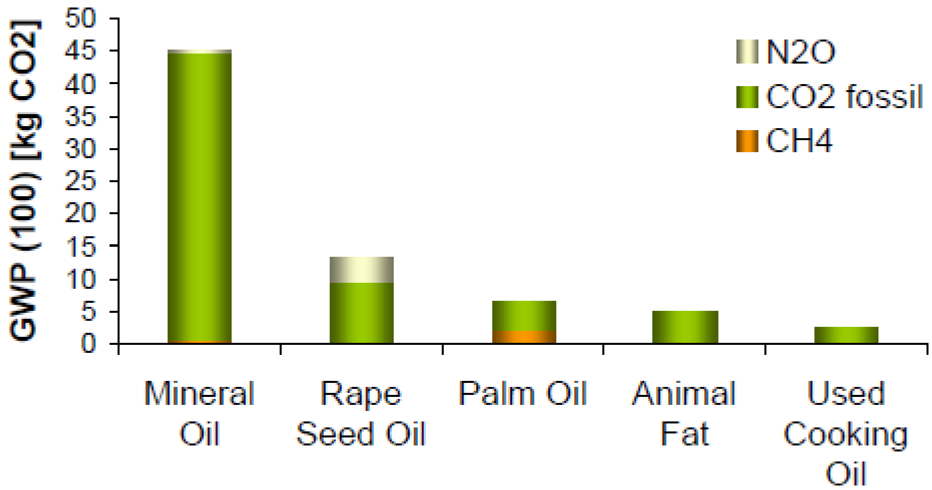


Figure 2.4: Global warming potential (GWP) (Source: Herrmann et al. 2007).

It was observed that the main disadvantage of native products based on plant seed oil is their relatively high market price as shown in Table 2.11. The authors noted the market prices in relations to the potential environmental impact and concluded that mineral oil product offered cheapest price while causing the biggest potential harm to the environment.

Table 2.11: Prices of coolants
(Source: Herrmann et al. 2007).

coolant based on	market price [€/kg]
mineral oil	1,35
plant seed ester	3,30
animal fat ester	2,26
used cooking oil ester	2,18

2.2.5 Limitation of cutting fluid in machining

There are typical examples where cutting fluids application in machining processes, whether it is vegetable or mineral based harm the process and therefore, it must be avoided. Example, cutting fluid should not be used when machining with ceramic tool as thermal shocks and tool breakage are likely to occur. But ceramic tool based on Si_3N_4 have higher toughness and the capacity to resist thermal shock that could lead to failure. Water based fluids could cause fire hazard when machining magnesium because the water can react with the chip form and release hydrogen, which is capable of causing ignition (Sales *et al.*, 2001). It is highly recommended that dry machining be adopted when machining with ceramic tool and straight oil can be used in the case of magnesium as metalworking fluid.

CHAPTER 3

3 Research Methodology and Materials

3.1 Experimental method for formulation of cutting fluid

3.1.1 Determination of selected properties of vegetable oils

Investigation of the oils properties in this study considered those properties that directly affect the use of oil as cutting fluid either as cutting oil or emulsion of oil-in-water (Krishna et al., 2010). The determination of physical and chemical properties of the two vegetable oils are necessary, as it serves as a guide in the type and quality of additives needed for oil-in-water emulsion cutting fluid formulation. Properties such as (i) fatty acid composition, (ii) free fatty acid, (iii) iodine value and (iv) effect of antioxidant agent on the oxidative and thermal stabilities of the two vegetable oils were determined at the laboratory of University of Kebaagsaan Malaysia (UKM- UNIPEQ). Other properties such as (i) flash point, (ii) pour point (iii) density and (vii) viscosity were determined at Malaysia Palm Oil Board, (MPOB) laboratory. Palm kernel oil and cottonseed oil were analyzed to determine their fatty acid composition using gas chromatography (GC- FID). Fatty acid composition of the oil was determined by preparing methyl esters of fatty acid using IUPAC 2.301 equal to MPOB p3.4 (acidic methanolysis method). The methylated samples were placed in autosampler (supelco 37 component, FAME mix, cat no: 18919) and 0.5 mL sample was injected into the GC (HP 5890 series II plus) equipped with a split injector flame ionization detector (FID)

3.1.2 Oxidative and thermal stabilities of PKO and CSO

The thermal decomposition of the two vegetable oils (PKO and CSO) with butylated hydroxytoluene (BHT) additive of 0.5 and 1.0% by volume were investigated. This study helped to understand the effect of additive (antioxidant) on the oxidative and thermal stabilities of the two vegetable oils. The experiment was conducted at UNIPEQ-UKM laboratory using Thermo-gravimetric analyzer (TGA -50, Shimdzu model) at 10 ^{o}C/min for between 30 and 600^{o}C constant heating rate. The purge gas used for testing the oxidative stability was oxygen at 100 mL/min rate of flow, while nitrogen was at the same flow rate to determine thermal stability. Oil sample of 10 g was used in platinum pans in each analysis. TGA curves obtained from an average of two independent measurements were used in the study of the oxidative and thermal stabilities of the oil samples. Table 3.1 shows the samples of oil used in this investigation.

Table 3.1: Oil samples for TG analysis

No	Sample 1	Sample 2
1	PKO	CSO
2	PKO + 0.5% C	CSO + 0.5% C
3	PKO + 1.0% C	CSO + 1.0% C

3.1.3 Pour point of PKO and CSO

Differential scanning calorimetry (DSC) experiment was carried out at UNIPEQ-UKM laboratory using DSC822E, Matter Toledo model with a computer-based controller. Low-pressure nitrogen gas was used to purge the DSC cell before each experiment. An accurately weighed of 10 g oil sample in an opened aluminum pan was used as reference point. While sample of oil was heated to 50^{o}C rapidly and then held for 10 minutes under isothermal condition. This process assist any present of waxy material in the oil to dissolve and homogenize, which equally serve as a seed to accelerate the formation of wax crystal during cooling. The system was then cooled from 50 to -50^{o}C at a steady rate of 10^{o}C/min using liquid nitrogen as the cooling medium.

3.1.4 Materials for formulation of cutting fluid

3.1.4.1 Vegetable and mineral oils

Two types of vegetable oils and one mineral oil were used in this study. There are palm kernel oil sourced from Malaysia and cottonseed oil sourced from Nigeria. While, mineral oil known as Mobilcut100 oil concentrate was sourced locally from Malaysia market.

(a) Palm kernel oil

The origin of oil palm (*elaeis guineensis*) can be traced to the tropical rain forest region of West Africa, along the Southern latitudes of Cameroon, Cote d' Ivoire, Ghana, Liberia, Nigeria, Sierra Leone, Togo and into the equatorial region of Angola and the Congo. The use of oil from palm fruits as edible oil has been on in African for well over thousands of years. The cultivation of palm oil has increased in geographical are by 43% as from 1990s to the present time. Seventeen countries produce lager quantity of palm oil, but the five top countries in the World are Indonesia, Malaysia, Thailand, Nigeria and Colombia, but Malaysia and Indonesia account for 85% of World production. About 41% of World palm oil production came from Malaysia and accounted for 47% of World export. Hence, Malaysia now accounts for 11% and 25% of the World's total production and exports of oils respectively. (http://chemicalland21.com/industrialchem/organic/palmitic%20acid.htm). Palm product accounts for 10 % of Malaysia gross domestic product (Maleque, 2003). Palm kernel oil is derived from the kernel of the palm (Poku, 2002) and there is a great different between edible oils obtained from palm fruits and coconut oil **(**Reeves and Weihrauch, 1979). The palm kernel oil (PKO) for this research work was sourced as refined palm kernel oil from Socship Company Sdn Bhd, Port Klang, Selangor, Malaysia.

(b) Cottonseed oil

Cotton has a very long history in Nigeria and its cultivation started well before the colonial era. It is estimated that about 1 million Nigerians are involved in the production and processing of cotton, which is grown by about 0.8 million small scale farmers on over 0.5 million hectares. Nigeria cotton is mainly rain fed and grows in the savanna region of the northern states in the areas extending from 7 to 13^{o}N latitude. The three major cotton producing zones in Nigeria are north-east, north-west and north-central. North-west and north-east are considered as the major producing zones and account for 60% and 35% of the crop respectively. Its cultivation is focused on textile industry (Reeves and Weihrauch, 1979). Cottonseed oil (CSO) for this research work was sourced from AFCOT Nigeria Plc, Ngurore along Numan – Yola, Adamawa State, Nigeria.

(c) Mineral oil

Mobilcut100 oil concentrate is a mineral based oil (MO) used in this study. Mobilcut is a trademark name for Mobil industrial lubricants and it is an industrial water miscible lubricant with high performance as metal removal cutting fluid. It is formulated with base oils and other additives. It is a non-chlorinated product and can be used for various machining processes. The concentrated oil has ability to form oil-in-water emulsion cutting fluids with either hard or soft water qualities. It has low foam potential and long-term corrosion inhibition for machining components. It is stable and can be used for all machine shops operation where better performance, low maintenance, health and environmental issues are critical factors in manufacturing process. The oil concentrate require mixing with water before application and readily mixes with water to foam emulsion that is stable for machining process (www.exxonmobil.com).

3.1.4. 2 Water quality requirement for cutting fluid formulation

Water quality is a fundamental requirement in the formulation of oil-in-water emulsion cutting fluid as it affects its stability and performance. Hardness of water is determined by the amount of calcium and magnesium salts in water that has effect on the emulsifier content in the formulation of oil-in-water cutting fluid. While soft water promotes unnecessary foaming, hard water lead to formation of water insoluble soap and this reduces the emulsifier content. Hence, the same water quality requirement for drinking water have been accepted or approved to meet requirement for formulation of oil-in-water emulsion cutting fluid as bacteria, yeasts and fungi level can be stabilized for the emulsion. Ong *et al*., (2007) conducted a survey on the quality of drinking water in Kuala Lumpur, which shows an acceptable standard with an average hardness level of 65 mg $CaCO_3$/l and an average of pH value of 7.72. The water for this research work was sourced from Kuala Lumpur Water Board. The summary of all the constituents of oil-in-water emulsion cutting fluid are shown in Figure 3.1.

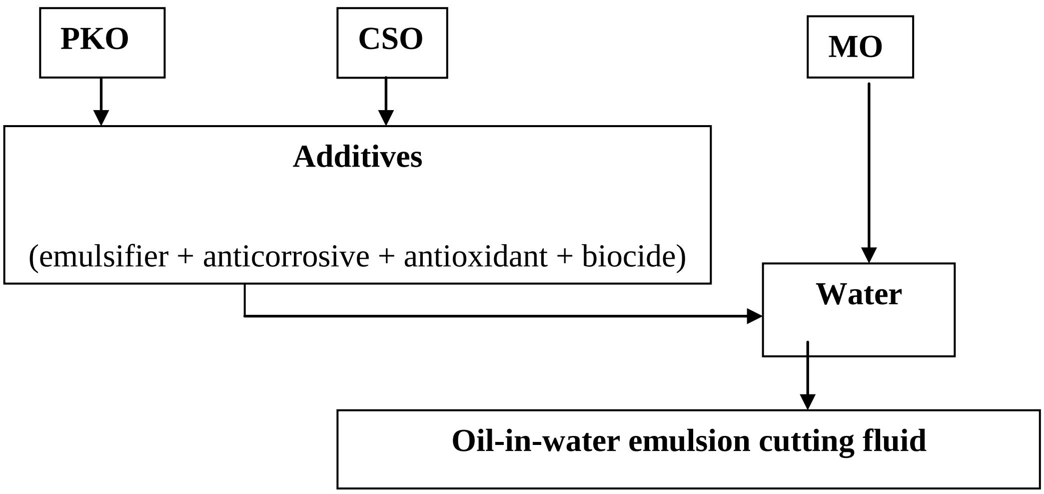


Figure 3.1: Constituents of oil-in-water emulsion cutting fluid

3.1.4.3 Additives

Additives are substances used in the formulation of cutting fluid to enhance the properties of base oils, which helps the lubricant performance and extending the equipment life. The recommended amounts of additives may be between 25 to 30 % in any formulation (Alves & de Oliveira, 2006). The preparation of cutting fluid may consist of any of these additives: biocide, emulsifier, antioxidant, corrosion inhibitors and friction modifiers etc. Hence, the following additives were used in this study to develop vegetable oil-based fully biodegradable cutting fluid that will offer good machining performance and significant benefits to the environment.

(a) Emulsifier

Emulsifier consists of two basic parts, one part is water soluble hydrophilic and the other is water-insoluble lipophilic. The hydrophilic part attaches itself to water and the lipophilic part attaches itself to oil whenever an emulsifier is added to oil and water mixture. There is an interface between surface of water and air in one hand and oil and air on the other hand and the hydrophilic part and lipophilic part are arranged around the interface. The emulsifier reduces the interfacial tension, that is, the force to separate the oil and water is weakened, which assist the mixing of oil and water very easy. Different emulsifiers have different hydrophilicity and lipophilicity and the relationship between the two is known as hydrophile-lipophile balance (HLB) value, which ranges from 0 to 20. The higher the lipophilicity, the lower the HLB value and the higher the hydrophilicity, the higher the HLB value. Emulsifier with too high hydrophilicity will disperse in water and the one with high lipophilic will disperse in oil. When the hydrophilicity and lipophilicity are well-balanced, the emulsifier exhibits sufficient effects. Polyoxyethylene (20) sorbitan monostrearate (Tween 60) sourced from R & M chemical marketing; Essex, UK was used for this study as an emulsifier. The ability of this emulsifier to form oil-in-water emulsion is defined in terms of the hydrophilic-lypophilic balance (HLB) value. Tween 60 is non-ionic surfactant with HLB value of 14.9. Its other properties are as follows: molecular weight: 1309, density: 1.044 g/mL at 25^{o}C and water solubility: 10 g/l.

(b) Anticorrosive agent

Ethanolamine as anticorrosive agent was chosen for this study because it can stabilize the oil emulsions. Its other properties are: density: 1.012 g/cm^3, acidity of 9.50 pKa, refractive index of 1.4539 (20^{o}C), vapour pressure of 64 Pa (20^{o}C), boiling point of 170^{o}C and melting point of 10.3^{o}C and molar mass of 61.08 g/mol.

(c) Antioxidant

The anti-oxidant agent used for this formulation is known as butylated hydroxytoluene (BHT) (Sigma-Aldrich~B1378 brand). It is a chain breaking antioxidants when used in metalworking fluids (MWFs). It possesses the following physicochemical properties at standard state of 25 ^{o}C and 100 kPa: density: 1.048 g/cm^3, melting point: 70 -73^{o}C, boiling point: 265^{o}C, solubility in water: 1.1 mg/L at 20^{o}C, flash point: 127^{o}C and molar mass: 220.35 g/mol.

(d) Biocide

The biocide agent used in this study belong to a family of triazine derivative (triclosan) used in cutting fluid formulation. It acts as an antibacterial and antifungal agent necessary for vegetable oil based cutting fluid formulation. Its properties are as follows: molar mass: 289.54 g/mol, density: 1.49 g/cm^3, melting point of between 55 -57^{o}C, boiling point: 120^{o}C, flash point: 162.2^{o}C at standard state of 25^{o}C and 100 kPa.

3.1.5 Formulation of cutting fluids using design of experiment

The need for simultaneous analysis of different parameters that affect system process became prominent in the implementation of industrial projects. Systems, products and processes optimization through the traditional procedure is able to establish experimental conditions that can be used when a large number of experiments are to be carried out (Box and Behnken, 1960). It has been established that design of experiment (DOE) method could minimize cost through the number of arrays involved in any experimental investigation. Maximal information can be obtained from the system being studied using rational and economic way during experimental planning. This method can be applied in the examination of process variables and their effects on the properties of the final product. In general, with n_1 levels for factor 1, n_2 levels for factor 2, ..., and n_k levels for factor *k*, the planning will result as (n_1 . n_2 ... · n_k) factorial. The simplest planning is devised when all factors are studied at two levels only. Therefore, with *k* variables being controlled by the analyst, a complete two-level planning requires the realization of 2^k different experiments (Hahn, 1993). Statistical method is then used to explain the output of the design in terms of effects on the unit factor variable. The experimental design helps to obtain information through the interaction or contour diagrams, which explain the relationships that exists between the factors and outputs. The dependence of the output (Y) analyzed with the experimental variables (x_i) can be approximated to a polynomial expression (equation 3.1):

$$Y = \beta_0 + \sum \beta_i x_i + \sum \beta_{ii} x_i^{\ 2} + \sum \beta_{ij} x_i x_j \qquad (3.1)$$

where β_0 is constant, β_i and β_{ij} are coefficient; x_i represents independent variables and x_{ij} denotes the interactions thereof (Montgomery, 2009).

In this study, the formulation of oil-in-water (O/W) emulsion cutting fluid from the two types of vegetable oils was based on design of experiment (DOE) of 2^4 full factorial with four variables (emulsifier, anticorrosive agent, antioxidant and biocide). Montgomery et al., (1998) observed that, when all process factors are known, the use of factorial design of experiment is possible by fixing the response to determine the effects of each variable on the performance of the process. Lower and upper limits were chosen based on information available from literature (Muniz et al., 2008; and Alves and Oliveira, 2006). The variable levels adopted for the experiment is shown in Table 3.2 in percentage by volume, while the experimental matrix of the 2^4 full factorial designs gives sixteen runs as shown in Table 3.3

Table 3.2: Variables and levels employed in the factorial design

Factor	Symbol	Level (% volume)	
		Minimum (-)	Maximum (+)
Emulsifying agent	A	8.0	12
Anticorrosive agent	B	2.0	4.0
Antioxidant	C	0.5	1.0
Biocide	D	0.5	1.0

Each run was formulated by first mixing oil in water with other additives as shown in Figure 3.2. This mixture was mixed together with the aid of mechanical stirrer at 760 rpm for 10 minutes at room temperature of 25 ^{o}C as shown in Figure 3.3.

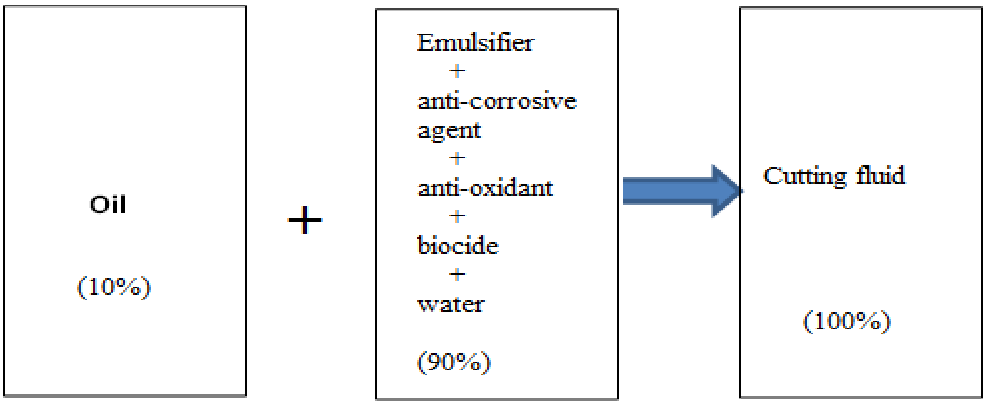


Figure 3.2: Mixture process

Table 3.3: 2^4 full factorial experimental design matrix

Array No	Variable levels			
	A	B	C	D
1	-	-	-	-
2	+	-	-	-
3	-	+	-	-
4	-	-	+	-
5	-	-	-	+
6	+	+	-	-
7	+	-	+	-
8	+	-	-	+
9	-	+	+	-
10	-	+	-	+
11	-	-	+	+
12	+	+	+	-
13	+	-	+	+
14	-	+	+	+
15	+	+	-	+
16	+	+	+	+

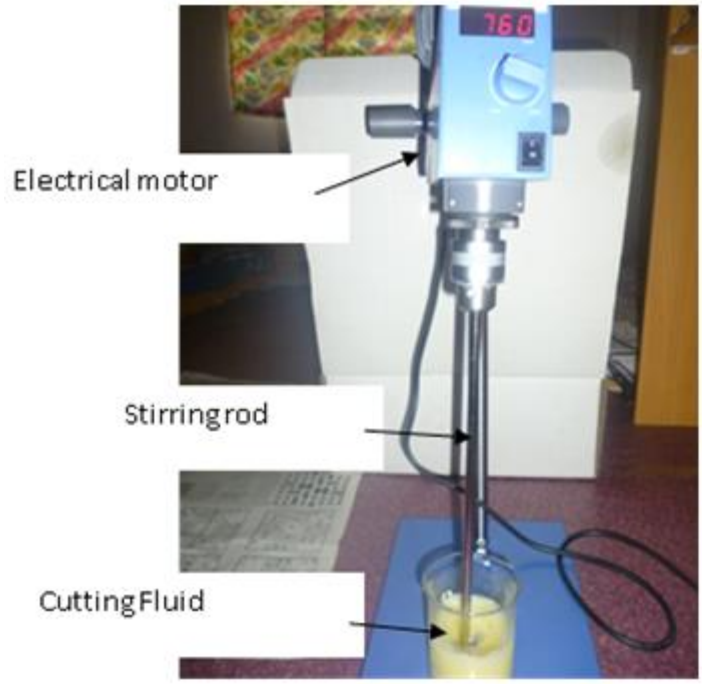


Figure 3.3: Mixing with mechanical overhead stirrer

3.1.5.1 Preliminary study

Preliminary study was conducted to establish the right proportion of oil to water ratio. The upper limit values of the additives were used in the preliminary study for the formulation. Stability as to percentage of water separation after twenty-four hours and pH values of the formulated fluids were determined at ratios of 5, 10 and 15% oils to 95, 90 and 85% of water respectively.

3.1.5.2 pH value

The pH values for the sixteen runs were measured with pH meter as shown in Figure 3.4. The pH meter was first calibrated with standard solution. After each reading, the electrode was cleaned with distilled water before taking another reading which was replicated for each run.

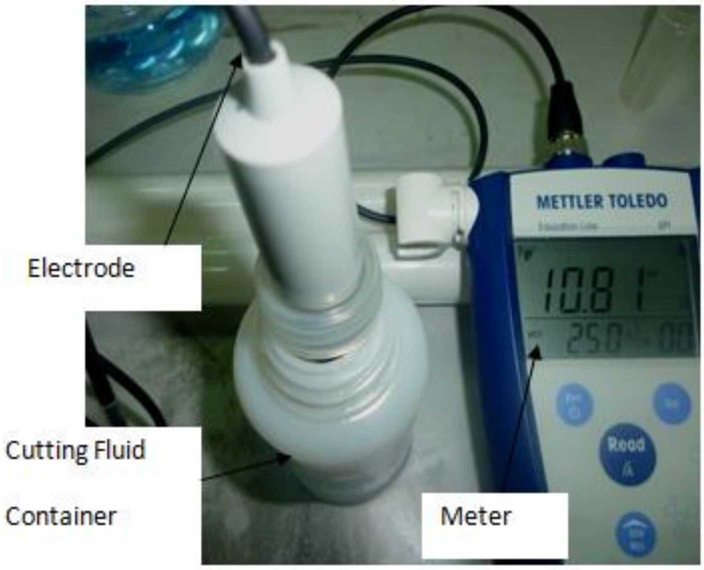


Figure 3.4: pH value measurement

3.1.5.3 Viscosity

The determination of viscosity involved the use of ASTM D445 and ISO 3104 method which was carried out in the Department of Chemical Engineering laboratory, Faculty of Engineering, University of Malaya. The oil or fluid sample was placed into a glass U-tube. The sample drawn through the tube using suction until it reached the starting position indicated on the tube under gravity. The suction was released to allow the sample to flow back through the tube under gravity. The resistance of the oil flowing under gravity through the capillary tube actually measured the oil's kinematic viscosity. An average of independent ten measurement of viscosity test conducted at temperature of 40^{o}C for each sample was reported.

3.1.5.4 Corrosion level

The corrosion level of oil-in-water emulsion cutting fluid was determined by using the method adopted by Alves and Oliveira (2006) as explained in subsection 2.1.3.1.

3.1.5.5 Stability

The stability of the vegetable oil-in-water emulsion cutting fluids was evaluated based on visual transparency within a period of 24 hours at room temperature (25^{o}C) as to phase separation in a graduated 100 mL test tubes.

3.2 Materials

3.2.1 Workpiece material

A round bar of AISI 4340 steel alloy with 90 mm diameter and 360 mm length was used as workpiece material for this study. AISI 4340 is a medium carbon, heat-treatable, oil-hardening, low alloy steel. The chemical composition and typical physical and thermal properties of AISI 4340 alloy steel are shown in Table 3.4 and 3.5 respectively.

Table 3.4: Chemical composition of AISI 4340 steel (wt %)

C	Si	Mn	P	S	Cr	Ni	Mo	Fe
0.425	0.343	0.692	0.014	0.007	0.850	1.461	0.220	95.95

Table 3.5: Typical physical and thermal properties of AISI 4340 steel

Parameter	Value
Tensile strength	882.61 – 1029.71 MPa
Yield strength	735.51 MPa
Hardening temp	830-860 ^{o}C
Soft anneal temp	710 ^{o}C
Hardness	270-310 HB

AISI 4340 steel is a high strength low alloy (HSLA) steel which is cheap, compared to expensive high alloy steels and it has an appropriate hardness value combined with a very high toughness and tensile strength. AISI 4340 alloy steel has gained wide acceptance in numerous industries for applications such as in shafts, gears, and aircraft landing gear production. It is also useful in any application where high strength, fatigue and creep resistance are needed, even at elevated temperature (Bejarano et al., 2008; McDaniel et al., 2008).

3.2.2 Cutting tool material

The TiN coated tungsten carbide, type: CNMA 12 04 08 - KR tool inserts were used for the experiment. TiN coating is extremely inert, as it does not have the ability to form an alloy with common metals, even under high operating temperatures. As a result, a TiN coating resists abrasion, adhesion, galling, welding, cratering and the formation of built-up edge, especially at lower cutting speeds (Rahman et al., 1996).

3.3 Experimental design and instrumentation

The experiment in this study was based on design of experiment (DOE) via Taguchi method and orthogonal array. Eighty one experiments were to be carried out but with the application of Taguchi method only twenty seven experiments were conducted to study the entire parameters space. This method will save both time and cost in experimentation. In this study, cutting speed, feed, depth of cut and types of cutting fluids were used as the input variables for the experiments. Hence, there were four input parameters each at three levels as shown in Table 3.6.

Table 3.6: Process parameters and their levels

Factor	unit	level 1	level 2	level 3
Cutting speed	m/min	160	200	250
Feed	mm/rev	0.18	0.24	0.32
Depth of cut	mm	1.0	1.75	3.0
Type of cutting fluids	mm^2 /s	2.97	1.04	0.87

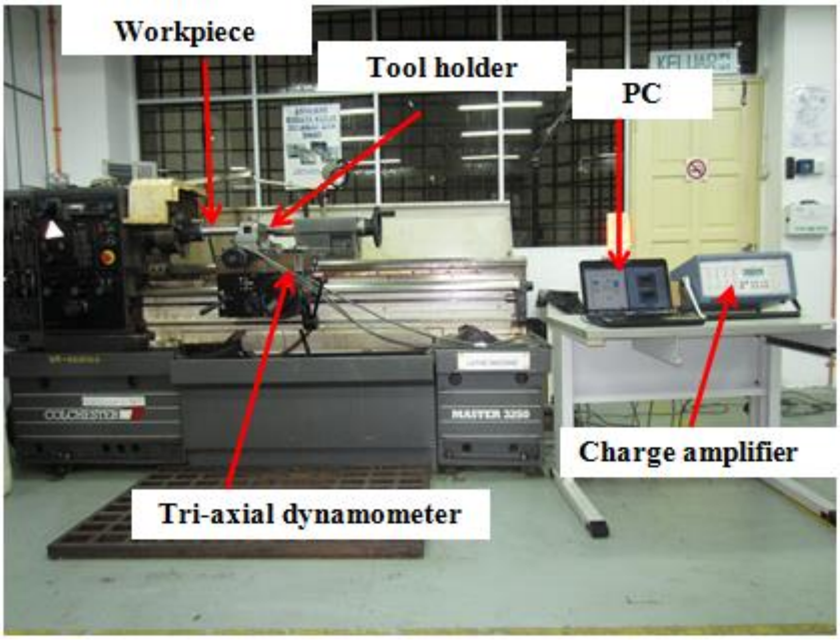
The actual cutting parameters used for each trial of experiment are shown in Table 3.7.

Table 3.7: Experimentation layout using an L_{27} orthogonal array

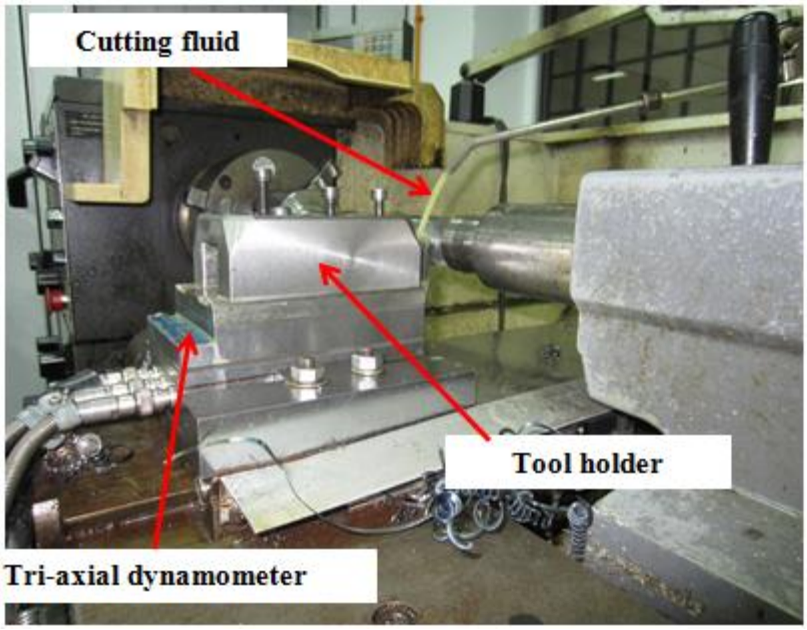
Trial No.	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Cutting fluids η (mm^2/s)
1	1	1	1	PKO
2	1	1	1	CSO
3	1	1	1	MO
4	1	2	2	PKO
5	1	2	2	CSO
6	1	2	2	MO
7	1	3	3	PKO
8	1	3	3	CSO
9	1	3	3	MO
10	2	1	2	PKO
11	2	1	2	CSO
12	2	1	2	MO
13	2	2	3	PKO
14	2	2	3	CSO
15	2	2	3	MO
16	2	3	1	PKO
17	2	3	1	CSO
18	2	3	1	MO
19	3	1	3	PKO
20	3	1	3	CSO
21	3	1	3	MO
22	3	2	1	PKO
23	3	2	1	CSO
24	3	2	1	MO
25	3	3	2	PKO
26	3	3	2	CSO
27	3	3	2	MO

PKO (palm kernel oil), CSO (cottonseed oil), MO (mineral oil)

Taguchi had specified L_{27} (3^4) orthogonal array for experimentation for a four factors, three levels experiment. The responses obtained from the experiments conducted as per L_{27} array experimentation were recorded and analyzed. The types of chips formed under various cutting fluids during turning process were accounted for. In this study, AISI 4340 steel was used as workpiece material and the cylindrical turning length to initial diameter ratio of workpiece was kept at 4 to ensure rigidity or stiffness required of chuck/ workpiece / cutting force. The TiN coated tungsten carbide CNMA 12 04 08 KR tool insert was mounted on a left hand tool holder with model number PSBNR 2525M12. The turning process was performed on a Colchester VS Master 3250 (165 mm x 1270 mm) gap bed centre lathe rated with 7.5 kW and spindle speed of 3250 rpm. In each experimental run a fresh cutting tool insert was used for a fixed cutting time of 15 minutes for each of the cutting fluids. The cutting fluid was applied using conventional (flood) method. Figure 3.5 shows the experimental setup for the experiment.



(a)



(b)

Figure 3.5: Experimental set up for turning process: (a) set up showing all components, (b) setup showing cutting fluid delivery

3.3.1 Cutting force

A tri-axial force dynamometer type: Kistler 9257A model was used to capture the force signals during the cutting process in *X*, *Y* and *Z* directions. The dynamometer consists of three-component force sensors fitted under high preload between a base plate and a top plate. Each sensor contains three pairs of quartz plates, one sensitive to pressure in the *Z* direction and the other two responding to shear in the *X* and *Y* directions respectively. The dynamometer has a great rigidity and consequently a high natural frequency of 3.5kHz. Its high resolution enables the smallest dynamic changes in large forces to be measured. The frequency range of the tri-axial force dynamometer is 10Hz – 400 kHz. Feed force (F_x), radial force (F_y) and main cutting force (F_z) were determined using a piezo-electric dynamometer (Kistler model 9257A) which was connected to charged amplifiers and a personal computer through an analog-to-digital converter card. LabView 2010 software with data acquisition (DAQ) system was used to obtain and record the force data. The amplitudes of dynamometer's amplitudes were calibrated with an accuracy of ± 126.95 N, ±126.95 N and ±278.5 N to measure the feed force (F_x), radial force (F_y) and machining cutting force (F_z) components respectively. The photograph of the experimental setup is shown in Figure 3.7. The cutting forces were derived from equation 3.5 and the lower the better characteristic was chosen for cutting force response.

$$F_r = \sqrt{F_x^{\ 2} + F_y^{\ 2} + F_z^{\ 2}} \qquad (3.5)$$

where F_r = resultant force; F_x = feed force; F_y = radial force and F_z = main cutting force.

3.3.2. Surface roughness

The surface roughness of the workpiece (AISI 4340 steel) was measured with the help of a stylus instrument. The equipment used for measuring the surface roughness was a portable surface roughness tester MAHR Perthometer M2Pi as shown in Figure 3.6. Three measurements were used for each sample and the average value was used for the analysis.

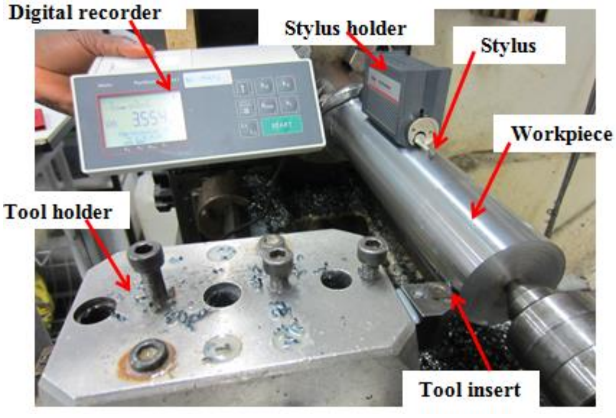


Figure 3.7: Set up for surface roughness measurement

The technical data for the device are:

Principle of measurement: stylus method

Measuring range (µm/µin): 100 /4000

Filter types: profile filter according to DIN4777 (digital, phase-corrected) RC-filter (digital).

Table 3. 8: MAHR Perthometer data sheet

Parameter		Value			
Cut –off length	(mm);	0.08	0.25	0.8	2.5
	(in)	0.003	0.01	0.03	0.1
Tracing lengths	(mm)	1.5	4.8	15.0	
	(in)	0.06	0.19	0.6	
Measuring length	(mm)	1.25	4.0	12.5	
	(in)	0.05	0.16	0.5	
Number of sampling lengths		1----5, selectable			

Parameters: Ra, Rz, Rmax, Rp, R_3z, Rz_{ISO}, P_L material ratio, three individual values, RzJIS, RmaxJIS.

3.3.3 Flank wear

The tool wear at the flank was observed and measured after each turning for 15 minutes using an optical microscope (DINOLITE AM7013MZT matel case, 5MP come polarizer). The microscope is equipped with software for measuring tool wear and investigating the microscopic picture of the tool insert of up to 250× magnification. An average of three reading measured at 50× magnification was reported. The setup for tool flank wear using DINOLITE optical microscope is shown in Figure 3.7

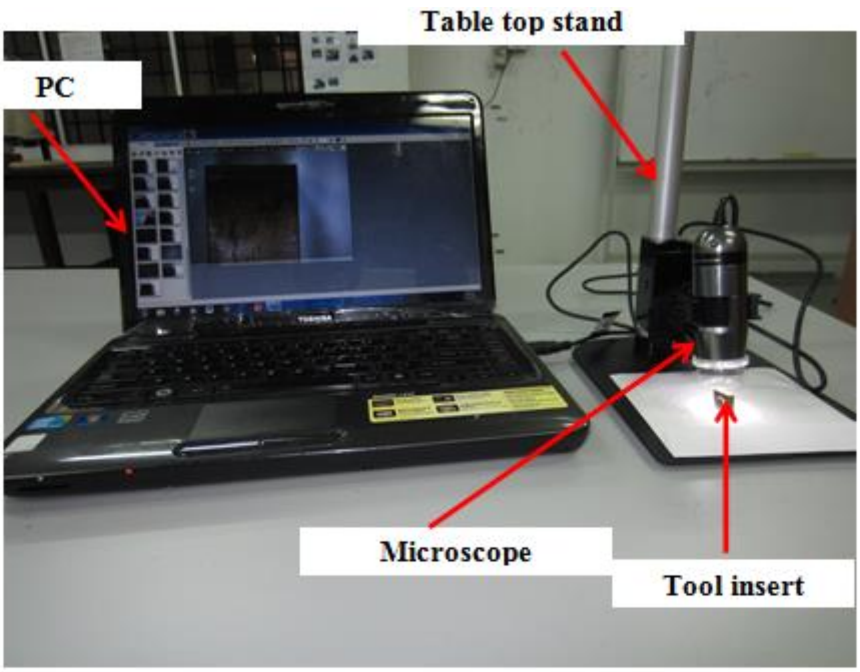


Figure 3.7: Microscope setup for tool flank wear measurement

3.3.4 Chip formation

The shape of chip is very important when high speed cutting and high productive cutting are employed. Though thick layers of material are removed very quickly and high productivity are achieved, but the quantity of chips increase. It has been observed that continuous chip takes a lot of space (Sutter, 2005; Filipowski & Marciniak, 2000). This type of chip causes problems when it's being removed from cutting zone and research also shown that improper form of a chip can cause faster consumption of cutting tool edge and its durability (http://www.sandvik.com/pl). It has been scientifically proved that a chip can be a source of important information about phenomena which are present during cutting process (http://www.sandvik.com/pl). Chip can therefore be used to monitor the process of cutting. The methods of application of cutting fluid into the cutting zone have significant impact on chip formation. The usage of cutting fluids causes the reduction of temperature of the tool and the workpiece which consequently affects the product precision, surface accuracy, blade durability, the friction, strength and power of cutting are lower, chips are removed more easily, the build-up is stopped, the workpiece and the cutting tool are protected against corrosion.

In order to understand the function of metal removal fluid, the knowledge of chip forming process is very important. Chip formation is due to shearing and sliding of a series of deformed layers of metal. The region where shearing takes place is known as shear plane. The sheared metal then slides over the rake face of the cutting tool. In addition to the machined part and chip, one of the primary products of the chip formation process is thermal energy or heat. This study therefore focuses on identification of types of chip formation during the turning of AISI 4340 steel with coated carbide tool under the three cutting fluids with respect to shape and colour.

CHAPTER 4

4 Results and Discussion

4.1 Properties of vegetable oils

The results of fatty acid composition, free fatty acid, iodine value, viscosity, pH value, flash point and density of the two oil samples are presented in this section. It has been established that the properties of any vegetable oils can be determined using their fatty acid composition. A high content of linoleic/linolenic acid decreases thermal-oxidative stability, whereas a higher proportion of long chain saturated fatty acids leads to inferior cold flow behaviour (Zeman et al. 1995). Jayadas and Nair (2006) observed that there could be loss of natural antioxidants during refining processes, which could lead to oxidative stability reduction. But this reduction in oxidative stability can be regained by the addition of suitable anti-oxidants.

The results of fatty acid composition for samples of two oil types shows that palm kernel oil (PKO) has an approximately 69.95% saturated fat with the main contributors being 44.06% lauric acid, 16.17% myristic acid and 9.52% palmitic acid. On the other hand, 20.96% of palm kernel oil is unsaturated fat with 17.91% oleic acid (monounsaturated) and 3.05% linoleic acid (polyunsaturated). Cottonseed oil (CSO) has approximately 10.43% saturated fat with the main contributor being 0.10% myristic acid and 10.31% palmitic acid, while about 80.01% is unsaturated with 29.24% oleic acid (monounsaturated) and 50.77% linoleic acid (polyunsaturated). The fatty acid composition or profile for the two samples of oil is shown in Table 4.1:

Table 4.1 Fatty acid composition of palm Kernel and cottonseed oils

Type of acid		Symbol	Fraction (%)	
Common Name	Formula		PKO	CSO
Lauric acid	$(CH_3(CH_2)_{10}COOH)$	C12:0*	44.06	0.0
Myristic acid	$(CH_3(CH_2)_{12}COOH)$	C14:0*	16.17	0.10
Palmitic acid	$(CH_3(CH_2)_{14}COOH)$	C16:0*	9.52	10.31
Stearic acid	$(CH_3(CH_2)_{16}COOH)$	C18:0**	2.58	0.02
Oleic acid	$(CH_3(CH_2)_7CH{=}CH(CH_2)_7COOH)$	C18:1**	0.0	29.24
Linoleic acid	$(CH_3(CH_2)_4CH{=}CHCH_2CH{=}CH(CH_2)_7COOH)$	C18:2**	17.91	50.77
Linolenic acid	$CH_3CH_2CH{=}CHCH_2{=}CHCH_2{=}CH(CH_2)_7CO_2H$	C18:3**	3.05	7.75
Others			0.92	1.81
Total unsaturated acids			20.96	87.76
Total saturated acids			69.75	10.43
Ratio of unsaturated / saturated			0.29	8.41

* saturated acids ** unsaturated acids

The gas chromatography of both vegetable oils is shown in Fig 4.1, while the detail data obtained from experiment is attached as appendix A. The chromatographic profile is a graphical representation of percentage composition of fatty acid in the oil

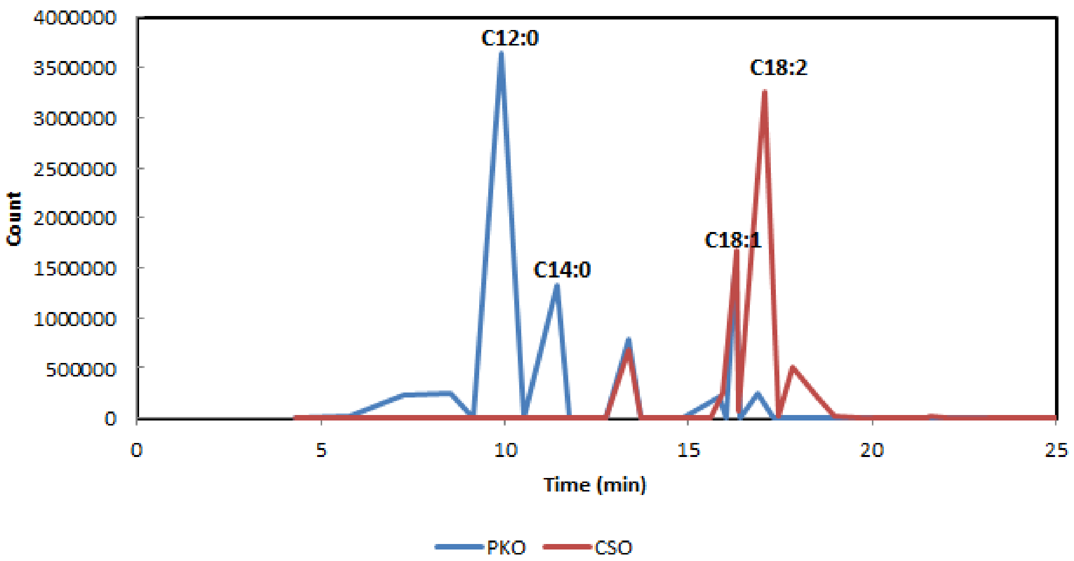


Figure 4.1: Gas chromatographic profile of palm kernel and cottonseed oils

As shown in Figure 4.1, PKO is a saturated oil with 44.06% of lauric acid (C12:0), 16.17% of myristic acid (C14:0) and while cottonseed oil is unsaturated oil with 50.77% linoleic acid (C18:2) and 7.75% linolenic acid (C18:3). This difference in fatty acid compositions of the two oils affect their behaviour when used in the formulation of cutting fluids for machining process.

Other selected properties of the two vegetable oils used in this study are shown in Table 4.2. Free fatty acid (FFA) is a pro-oxidant property and contributes to the decreased shelf life of oil. The present of significant amounts of FFA in oil will make smoking excessive; hence, such oil must be discarded if it is to be used as oil without mixing with water. In this study, the value of FFA for PKO (5.62) is higher than CSO (0.92). However, because the two oils were emulsified with water using additives, the excessive smoke and other disadvantages pose by higher FFA in oil are irrelevant in this study.

Table 4.2 Selected physical properties of palm kernel and cottonseed oils

Property	Palm kernel oil	Cottonseed oil	Method
FFA (% palmitic acid)	5.62	0.92	AOCS (1997)
Iodine value	17.12	17.40	AOCS (1997)
Flash point	205.4 ^oC	212.5 ^oC	ASTM D 93
Pour point	21.0 ^oC	-9.0 ^oC	ASTM D97
Density @ 15^{o}C	-	0.92 g/cm^3	ASTM D4052
Viscosity @ 40^{o}C,	28.89 mm^2/s	31.41 mm^2/s;	ASTM D445

The iodine value is a measure of unsaturation in oil. Flash point is the lowest temperature at which application of an igniter causes the vapour of a specimen to ignite under the specified test conditions. Pour point of oil is the most important low-temperature property of oil used as lubricant or cutting fluid and viscosity of oil is important parameters with respect to fluid performance and maintenance. The higher the viscosity the better the lubricating property and difficult in maintenance. In this study, all of these selected properties do not have direct effect on the formulated cutting fluid based on the two vegetable oils. This is because the addition of four additives in the formulation process altered the chemistry of the oils.

4.2 Oxidative and thermal stabilities of PKO and CSO

Oxidative stability is the resistance of a lubricant to molecular breakdown or rearrangement at elevated temperatures in ordinary air environment. Lubricating oils can oxidize when exposed to air, particularly at elevated temperatures, and this has a very strong influence on the life of the oil. The rate of oxidation depends on the degree of oil refinement, temperature, presence of metal catalysts and operating conditions (Klaus et al.1985; Colclough, 1987). One of the ways of improving oxidative stability is by adding additives. Vegetable oils are known to have poor oxidative, low thermal and hydrolytic stabilities and poor low temperature characteristics **(**Adhvaryu & Erhan, 2002; Zeman et. al., 1995, Gapinski et al., 1994, Becker and Knorr, 1996) primarily due to the presence of bis-allylic protons. These active sites are highly susceptible to radical attack and subsequently, the molecules undergo oxidative degradation and form polar compounds. This phenomena eventually results in insoluble deposits and increases in oil acidity and viscosity.

Figure 4.2 shows the TGA curves for the samples of PKO with and without additive under nitrogen and oxygen environment. An onset temperature of degradation of 275°C was observed for all the samples in oxygen environment and a significant weight gain of 38% at 300°C was notice for all the samples. It shows that the weight of the samples remains constant before the decomposition of its content began.

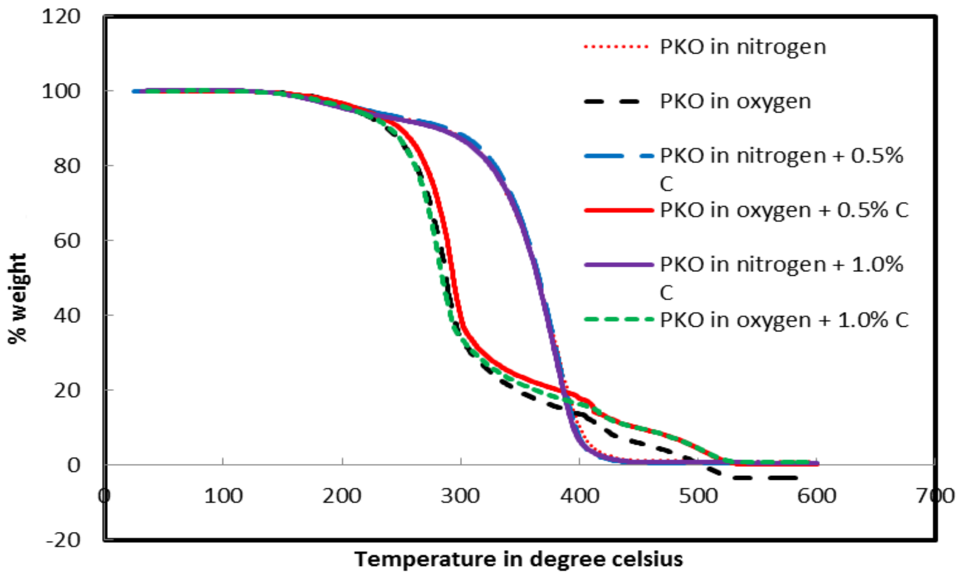


Figure 4.2: TGA curves under oxygen and nitrogen environment for PKO

It can be concluded that there is no effect of antioxidant on oxidative stability of palm kernel oil. This may be due to higher proportion of long chain saturated fatty acid of PKO, which made it to be more thermo-oxidative stable compared with vegetable oils with linoleic and linolenic acids (short chain fatty acids). (Jayadas and Nair, 2006). It can be observed that the addition of additive has no effect on the thermal stabilities of the oil samples.

The comparison of TG curves for the samples of CSO with and without additives under nitrogen and oxygen environments are shown in Figure 4.3. The onset temperature for all the samples in oxygen environment was observed to have taken place at 207°C, but there is a significant weight gain in the temperature range between 207 and 550°C.

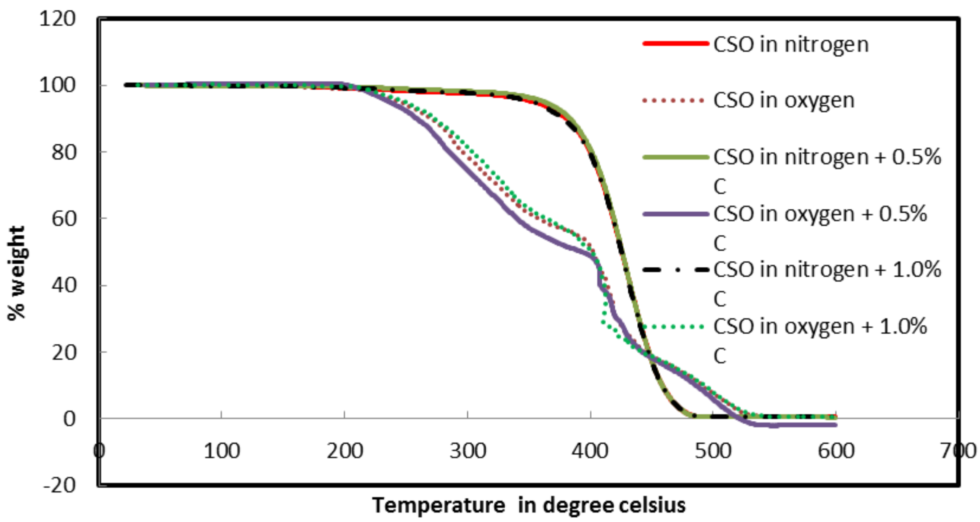


Figure 4.3: TGA curves under oxygen and nitrogen environment CSO

An approximate weight gain of 41% was observed for CSO + 0.5 C (antioxidant) at a temperature of approximately 400°C compared with 22% weight gain for CSO + 1.0 C (antioxidant) at 400°C. Hence, CSO + 0.5% C shows better oxidative stability compared with other samples. Similarly, it was observed that an addition of additive does not have any effect on the thermal stability of the oil samples.

Figure 4.4 compares the TGA curves under nitrogen and oxygen environment for both palm kernel and cottonseed oils without additives. As expected, palm kernel oil with high saturated fatty acid composition shows better oxidative stability as compare to cottonseed oil with high percentage of unsaturated fatty acid content.

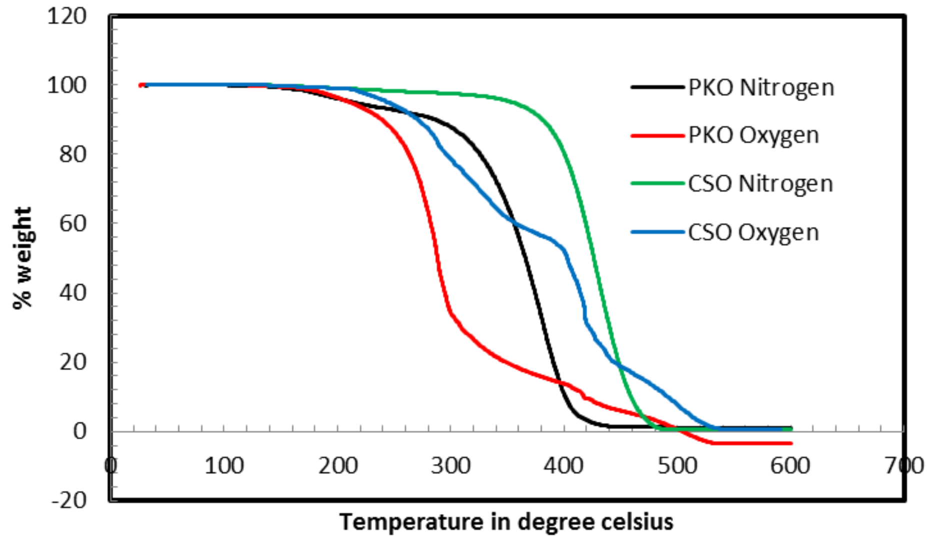


Figure 4.4: TGA curves under oxygen and nitrogen environment for PKO and CSO

The onset temperature of decomposition for both PKO and CSO are lower under oxygen environment, but there was weight gain between temperature ranges of 180 - 500^{O}C due to formation of oxidation products. The weight gain for PKO at approximately 300^{o}C is around 25% compared with weight gain by CSO at 450^{o}C which is about 18%. Due to the saturated nature of PKO, it show a better oxidative stability compared with CSO which is in agreement with literature (Jayadas and Nair, 2006).

4.3 Pour point of PKO and CSO

Plots of heat flow against temperature as the oil sample cooled from 50 to -50^{0}C are shown by DSC curves. The process involved the heating of oil samples to 50^{o}C and allow it to cool to -50^{o}C. Solidification is an exothermic reaction, therefore as heat flow out increases, solidification starts. Due to different fatty acid composition of vegetable oils, their solidification takes place over certain range of temperature. As shown in Figure 4.5 DSC curves of the two vegetable oils with and without additives show an exothermic peak as it cooled and the temperature at which the exothermic peak occurs correlate with the pour point of the oil samples. The pour point of oil is the most important low-temperature property of oil used as lubricant or cutting fluid. As shown in Table 4.3, it can be deduced that the addition of antioxidant agent has no effect on the pour point of the oil samples as the exothermic peak are very close for all the samples of the two oils.

Table 4.3: Result of pour point

S/N	Oil	Temperature (^oC) of occurrence of exothermic peak	Heat flow (mW)
1	PKO	10.15	6.69
2	PKO + 0.5% C	10.16	7.0
3	PKO +1.0% C	10.1	4.16
4	CSO	-9.97	1.71
5	CSO + 0.5% C	-9.97	1.63
6	CSO +1.0% C	-9.96	1.94

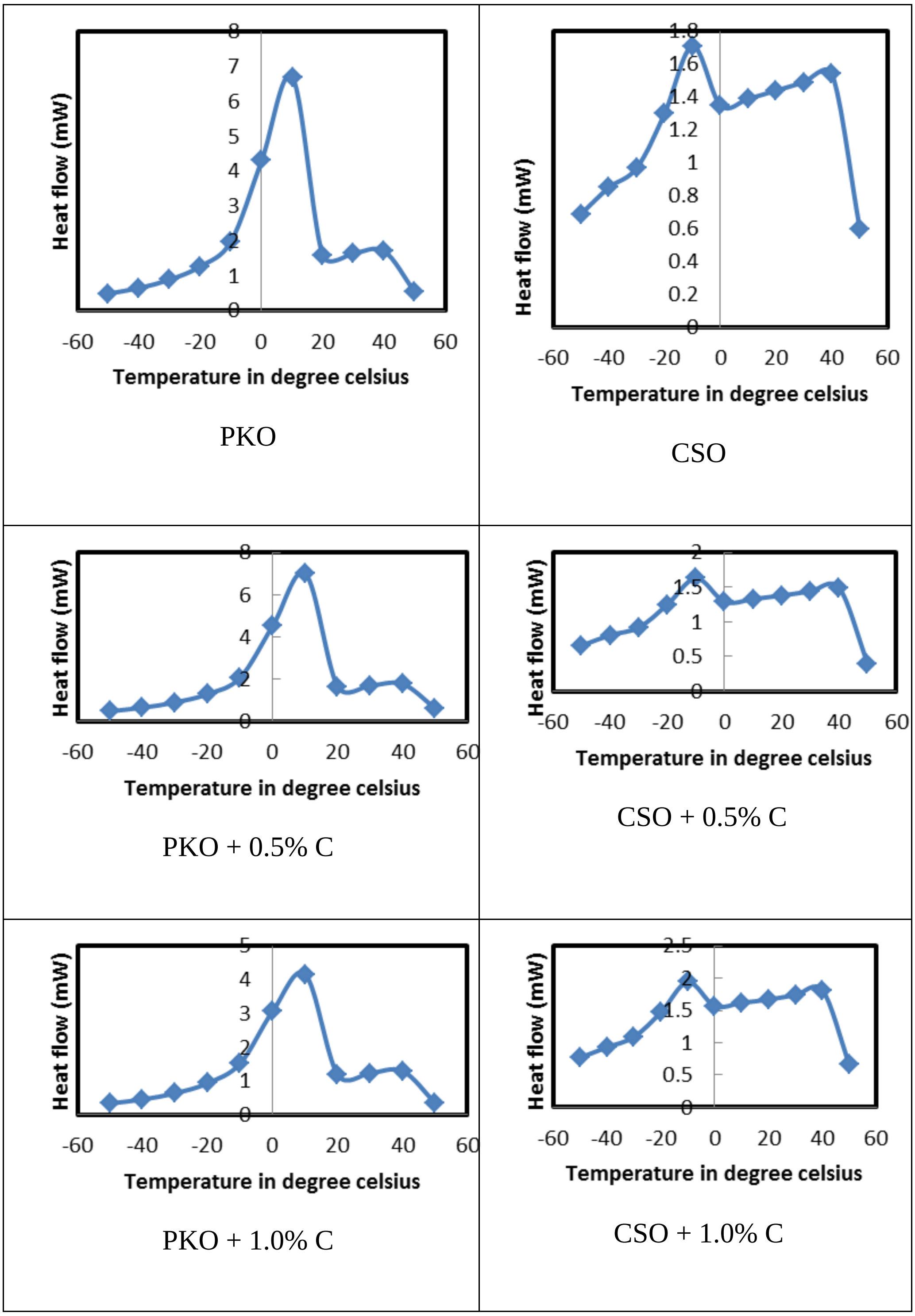


Figure 4.5: DSC curves for PKO and CSO with and without additives

4.4 Formulation

4.4.1 Preliminary study result

The ratios of oil to water in the formulations of oil-in-water emulsion cutting fluids using PKO and CSO were fixed at 5, 10 and 15% of oil to 95, 90 and 85% of water. Though, 5% of oil shows more stability than other samples of oils in this study, the pH value is too high. In the same vein, the pH values of 15% of oil samples were within acceptable level but with poor stability. Therefore, 10% ratio of oil was adopted for this study for both types of oils because both the pH values are within the acceptable range and the stabilities are relatives stable as shown in Table 4.4. The oil to water ratio in the formulation of cutting fluid can be influenced with quantity of emulsifier and quality of water (Rao *et al*. 2008).

Table 4.4: Results of stability (as percentage of water separation) and pH values

	PKO (%)			CSO (%)		
	5	10	15	5	10	15
pH value	12.5	10.6	10.2	11.92	10.7	9.8
Stability	98.2	97.0	94.0	98.0	96.8	95.0

4.4.2 pH value and ANOVA analysis for cutting fluid

The pH value of cutting fluid is a critical parameter used to study the corrosive nature of fluid, its potential to cause dermatitis and control of biological growth of cutting fluid. After each run has been submitted to all the processes of formulation, the pH value of each run was determined as the response of the process.

(a) Cutting fluid from palm kernel oil

Table 4.5 shows the average of the two runs obtained for the response of each run for oil-in-water emulsion formulated from palm kernel oil. The data obtained for the pH values for all the experiments were analyzed using statistical tools (DOE® software version 6). Second degree polynomial approximated by equation 3.1 was used by the software for the analysis to predict the response, Y, which includes all factors and the way they relate.

Table 4:5: pH value of 2^4 full factorial with random run order indicated

Run	A	B	C	D	pH value
1	8	2	1	1	10.43
2	12	4	0.5	0.5	10.88
3	12	4	0.5	1	10.75
4	8	2	0.5	1	10.69
5	8	2	1	0.5	10.74
6	8	4	1	0.5	10.83
7	12	2	0.5	0.5	10.57
8	12	2	1	1	10.52
9	12	4	1	0.5	10.74
10	8	4	0.5	1	10.69
11	8	4	0.5	0.5	10.84
12	12	2	1	0.5	10.62
13	12	4	1	1	10.74
14	8	4	1	1	10.73
15	12	2	0.5	1	10.72
16	8	2	0.5	0.5	10.79

The statistical check for this model reveals that the model is adequate, specifically, 93.28 % of the observed variability in the reduction pH model can be explained by the model terms in Table 4.6.

Table 4.6: Analysis of variance (ANOVA) for the pH value model

Source	Sum of Squares	DF	Mean Square	F- Value	Prob > F	Remark
Model	0.213	13	0.016	32.769	0.03	significant
A	0.003	1	0.003	4.999	0.155	insignificant
B	0.078	1	0.078	156.8	0.006	significant
C	0.021	1	0.021	42.05	0.023	significant
D	0.034	1	0.034	68.45	0.014	significant
AB	0.004	1	0.004	7.2	0.115	insignificant
AC	0.00003	1	0.00003	0.05	0.844	insignificant
AD	0.021	1	0.021	42.05	0.023	significant
BC	0.007	1	0.007	14.45	0.063	insignificant
BD	0.00003	1	0.00003	0.05	0.844	insignificant
CD	0.005	1	0.005	9.8	0.088	insignificant
ABC	0.007	1	0.007	14.45	0.063	insignificant
ABD	0.007	1	0.007	14.45	0.063	insignificant
BCD	0.026	1	0.026	51.2	0.019	significant
Residual	0.001	2	0.0005			
Total	0.214	15				

The statistical values in Table 4.7 are generated for R^2, adj. R^2, pred.R^2 and adequate precision.

Table 4.7: Statistical value for PKO cutting fluid

Statistic	value
R^2	0.9953
Adjusted R^2	0.9650
Predicted R^2	0.7009
Adequate Precision	21.275

The analysis of variance (ANOVA) for pH value in Table 4.6 shows that the model is significant as the model value is less than 0.05. Noticeably, anticorrosive agent (B), antioxidant (C) and biocide (D) are the factors that have direct significant effect on the pH value, while the interactions of emulsifier (A) and biocide (D); anticorrosive agent

(B), antioxidant (C) and biocide (D) have significant effect on the pH value. The statistical check for this model reveals that the model is adeqaute, specifically, 99.35 % of the observed variability in the reduction pH value model can be explained by the model terms in Table 4.6 The analysis yielded a "Pred *R*-Squared" of 0.7009, which is in reasonable agreement with the "Adj *R*-Squared" of 0.9649. The Model *F*-value of 32.77 shows that the model is significant. There is only a 3.00 % chance that a "Model *F*-Value" this large could occur due to noise. On analysis of the data, a prediction equation for the response was obtained as shown in equation 4.1.

$$\begin{aligned} pH &= 10.71 - 0.012*A + 0.70*B - 0.036*C - 0.046*D + 0.015*A*B \\ &- 1.25\times10^{-3}*A*C + 0.036*A*D + 0.021*B*C - 1.25\times10^{-3}*B*D \\ &- 0.018*C*D - 0.021*A*B*C - 0.021*A*B*D + 0.040*B*C*D \end{aligned} \qquad (4.1)$$

Figure 4.6 show the normal distribution plots with scatter points evenly distributed over and below a central line of fit. The statistical implication of this is that the errors in the experiments had constant variance and that there is little noise factor (about 0.01%) that might have influenced pH model during the experimentation.

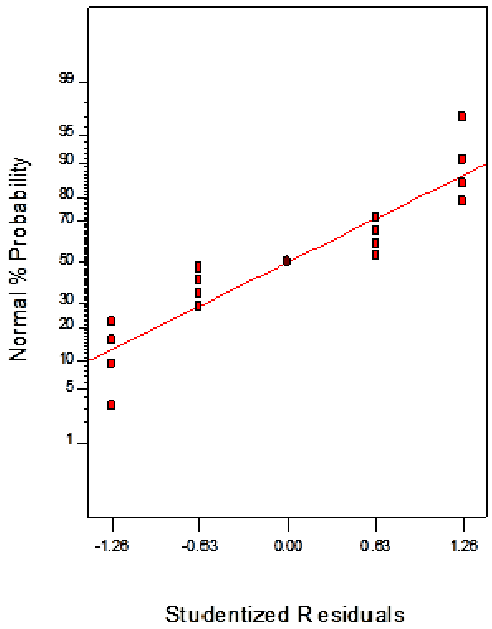


Figure. 4.6: Normal distribution plot for PKO cutting fluid

Residual points that show the residuals on the vertical axis and the independent variable on the horizontal axis were plotted for both predicted and run. It was observed in Figure 4.7, that all the points in a residual plot are randomly dispersed around the horizontal axis and within the band (studentized residual) of ± 3.0 deviation.

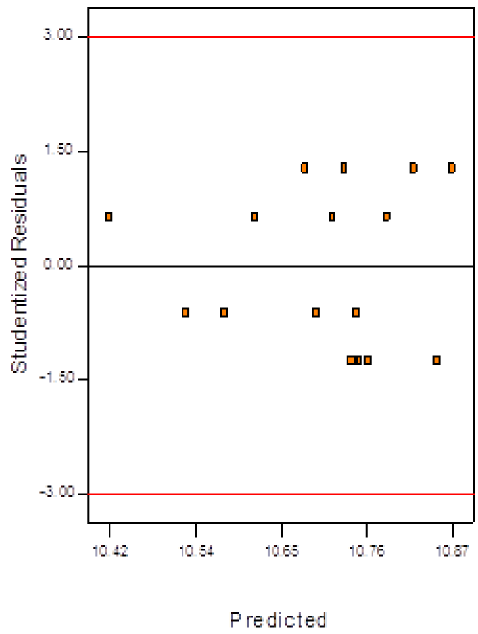


Figure 4.7: Residual plot used to check the errors for PKO cutting fluid

The plot show fairly random pattern as half of the residual points are located on the positive side of the horizontal line and the remaining half are below the horizontal line. It was observed that the residual points are more concentrated between the predicted pH value of 10.65 and 10.87 than between pH value of 10.42 and 10.54. This random pattern indicates that a linear model equation is appropriate for the data as there is no outliner.

In the same vein, it can be observed that Figure 4.8 showing residual plot versus run has similar trend compared with residual versus predicted plot except that the residual points are evenly distributed between run 1 and run 16.

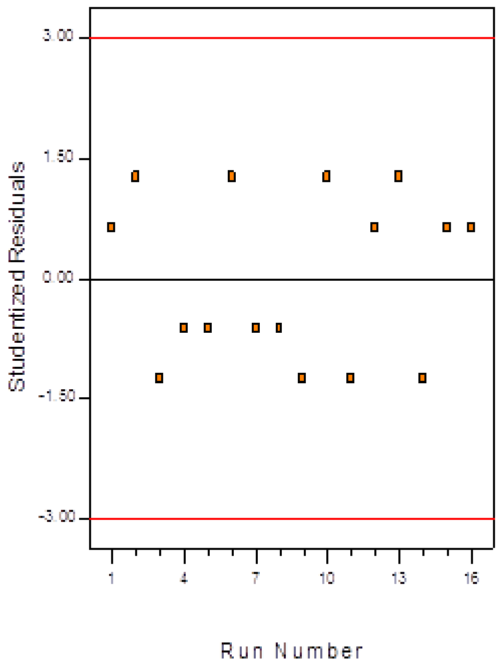


Figure 4.8: Residual plot to check for independence for PKO cutting fluid

It was equally observed that half of the residual points are located on the positive side of the horizontal axis and the remaining half located below the horizontal axis. It can be concluded that since all plotted points fall within the acceptable range of control without outliners, linear regression model equation is appropriate for the data.

The scatter plot in Figure 4.9 shows all values that cannot be fitted by the model. It is observed that the points are fairly and evenly distributed along the central line of fit.

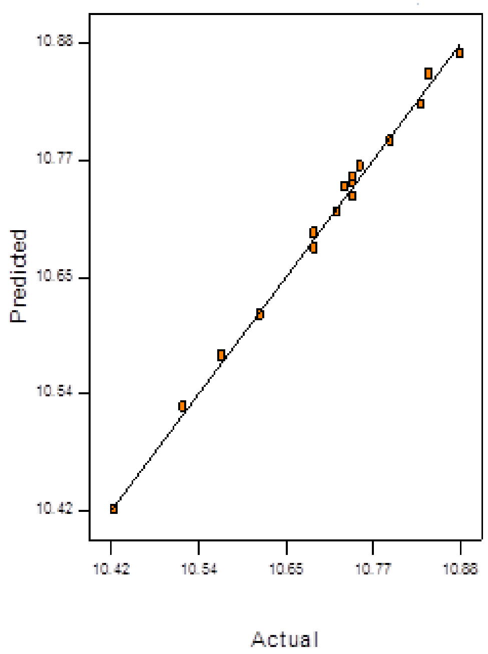


Figure 4.9: Scatter plot of predicted against actual for PKO cutting fluid

The contour plot shown in Figure 4.10 defines the acceptable and non-acceptable regions within which formulation should or should not be made. For instance, the region above the pH value of 10.66 contour line suggests unacceptable values of the biocide. While the 10.69 contour line is constant over a range of emulsifier quantity, a sharp drop is noticed as the quantity of the emulsifier approached about 11.4% value. This is an important turning point which tends to enclose the region of acceptability.

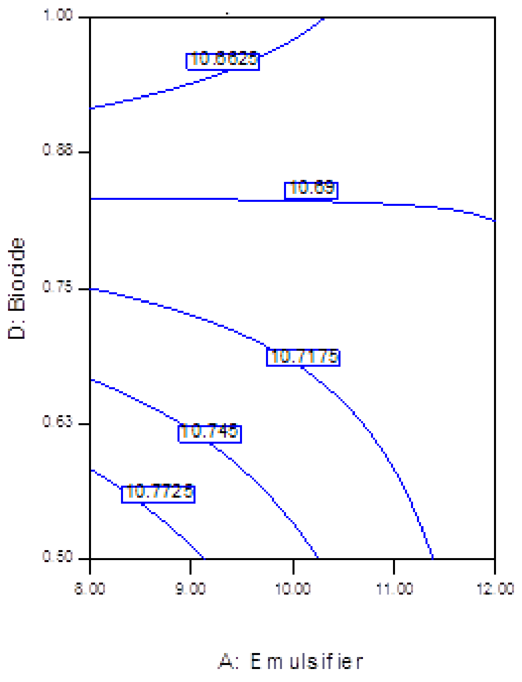


Figure 4.10: Contour plot for PKO cutting fluid

It was also observed that there exist interaction between emulsifier (A) and biocide (D) on the pH model as depicted in Fig 4.11. The pH value changes at different rates. As the quantity of emulsifier (A) increased from 8 to 12 %, and biocide (D) increased gradually to its maximum recommended level (1%), they both interact to bring the pH value of the formulated cutting fluid to 10.69. At this optimal point, the optimal value of biocide stood at 0.8% while that of the emulsifier was 11.4%. Interaction between these two factors (biocide and emulsifier) is indicated in the plot by the convergence of the two lines, with the red line representing emulsifier and the black representing the biocide. However, no attempt was made to study the chemical nature of the interaction between the emulsifier and biocide as this is outside the scope of the research as pointed out in subsection 1.4.

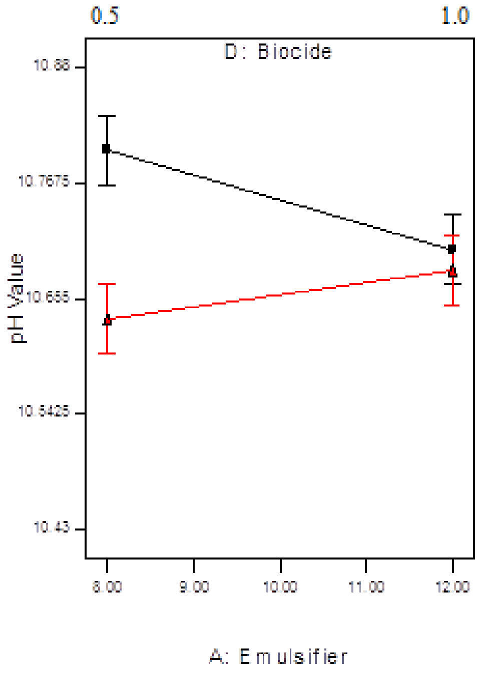


Figure 4.11: Interaction plot for PKO cutting fluid

(b) Cutting fluid from cottonseed oil

Table 4.8 shows the average of the two runs obtained for the response of each run for oil-in-water emulsion formulated from cottonseed oil. The analysis of variance (ANOVA) for pH value in Table 4.9 shows that the model is significant as the model value is less than 0.05. Noticeably, emulsifier (A) and anticorrosive agent (B) factors show significant effect on the pH value.

Table 4.8: pH value of 2^4 full factorial with random run order indicated

Run	A (%)	B (%)	C (%)	D (%)	pH value
1	12	2	1	1	10.81
2	8	4	1	0.5	11.09
3	8	4	1	1	11.02
4	12	2	0.5	0.5	10.81
5	8	4	0.5	1	11.06
6	12	2	1	0.5	10.78
7	8	4	0.5	0.5	11.17
8	8	2	1	0.5	10.86
9	12	4	0.5	1	11.05
10	8	2	0.5	0.5	10.91
11	12	4	0.5	0.5	11.04
12	8	2	1	1	10.86
13	12	2	0.5	1	10.8
14	12	4	1	0.5	11.02
15	12	4	1	1	11.04
16	8	2	0.5	1	10.83

Table 4.9: Analysis of variance for the model

Source	Sum of squares	DF	Mean Square	F Value	Prob>F	Remark
Model	0.227	4	0.057	53.037	< 0.0001	significant
A	0.013	1	0.013	11.829	0.006	significant
B	0.209	1	0.209	195.634	< 0.0001	significant
C	0.002	1	0.002	2.109	0.174	insignificant
D	0.003	1	0.003	2.576	0.137	insignificant
Residual	0.012	11	0.001			
Total	0.239	15				

The statistical check for this model reveals that the model is adeqaute, specifically, 93.28 % of the observed variability in the reduction pH model can be explained by the model terms in Table 4.9. The statistical values in Table 4.10 are generated for R^2, adj. R^2, pred.R^2 and adequate precision.

Table 4.10 Statistical value for CSO cutting fluid

Statistic	value
R^2	0.9507
Adjusted R^2	0.9328
Predicted R^2	0.8957
Adequate Precision	18.3211

The analysis yielded a "Pred R-Squared" of 0.8957, which is in reasonable agreement with the "Adj *R*-Squared" of 0.9328. The Model *F*-value of 53.04 implies the model is significant. There is only a 0.01% chance that a "Model *F*-Value" this large could occur due to noise. on analysis of the data, a prediction equation for the response was obtained as shown in equation 4.2.

$$pH = 10.95 - 0.028 * A + 0.11 * B - 0.012 * C - 0.013 * D \qquad (4.2)$$

Figure 4.12 show the plot of the normal distribution of the residual point. The plot show scatter points evenly distributed over and below a central line of fit. The statistical implication is that all the points had constant variance of experimental errors less than 0.01.

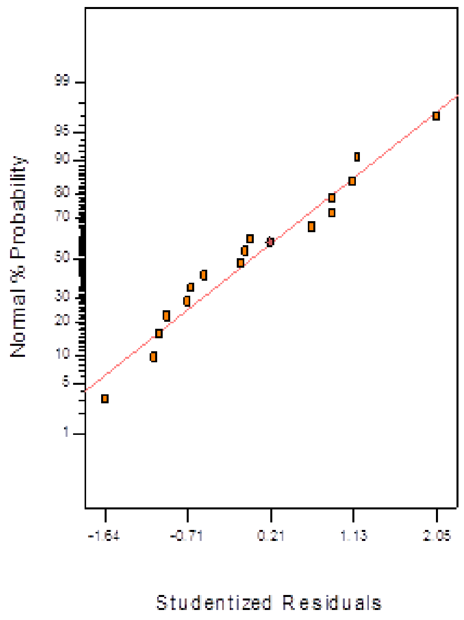


Figure 4.12: Normal distribution for CSO cutting fluid

The residual points on the residual versus predicted plot as shown in Figure 4.13 shows all points are randomly dispersed around the horizontal axis and within the band (studentized residual) of ± 3.0 without outlier.

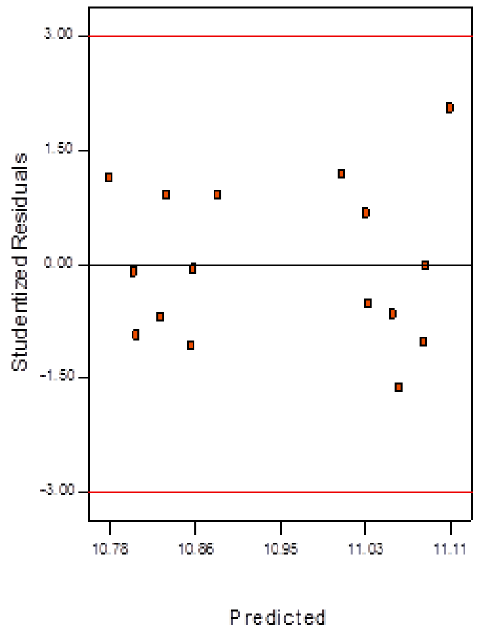


Figure 4.13: Residual plot used to check the errors for CSO cutting fluid

The points are more concentrated at both ends of the predicted values. Hence, the random pattern of these points indicates that a linear model equation is appropriate for the data. Figure 4.14 shows the residual plot versus run in which the all the points fall within the band of ± 3.0. The residual points are evenly distributed along the runs which make it possible for linear regression model equation to be appropriated for the data.

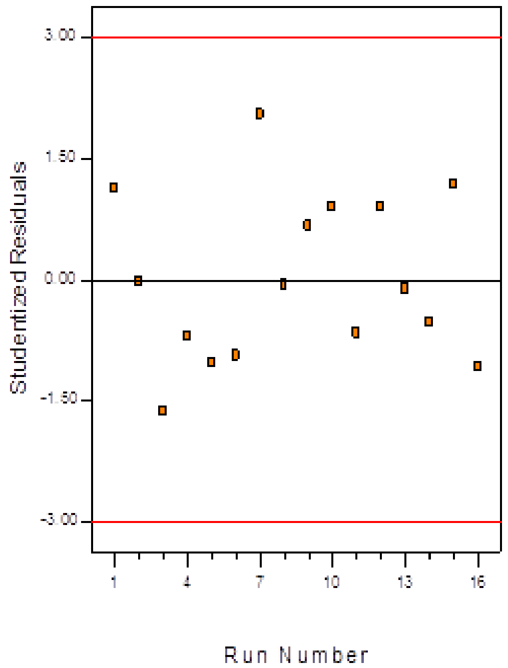


Figure 4.14: Residual plot to check for independence for CSO cutting fluid

The scatter plot in Figure 4.15 shows all values that cannot be fitted by the model. It is observed that the points are fairly and evenly distributed along the central line of fit and therefore, the statistical implication of the errors is about 0.01%.

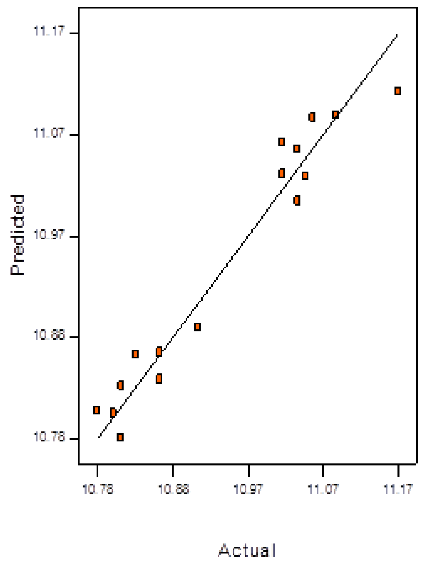


Figure 4.15: Scatter plot of predicted against actual values for CSO cutting fluid

Figure 4.16 shows the contour plot, which depicts the effect of emulsifier and anticorrosion terms on the pH value. It can be deduced from the plot that when the emulsifier level increases from 8.0 to 12.0% with increase in anticorrosive agent from 2.0 to 4.0%, the pH value increase. The chemistry reaction between emulsifier and anticorrosive agent is outside the scope of this work as reported in subsection 1.4

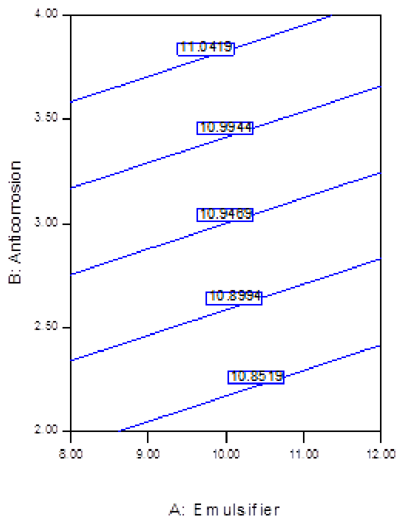


Figure 4.16: Contour plot for CSO cutting fluid

(c) Cutting fluid from mineral oil

The preparation of mineral oil based cutting fluid was carried out using the same percentage volume of oil and water ratio with that of palm kernel and cottonseed oils. The basic difference in the formulation process is the absence of any addition of additives to the formulation of mineral oil. The mineral oil used was concentrated oil but the details on the type and quantity of the consistuents are not available from the supplier

4.4.3 Optimization process and confirmation test

The optimal levels of the design parameters for formulation process for palm kernel and cottonseed oils based cutting fluids were selected based on desirable effect with the help of DOE software. In order to establish the quality characteristics using the optimal level of the design parameters, confirmation experiments were conducted to validate the pH value of the optimal parameters.

(a). Palm kernel oil based emulsion cutting fluid.

When the system was optimized for the pH value of oil-in-water emulsion cutting fluid formulated from palm kernel oil based fluid, the most desirable optimal values for the formulation process variables are as follows: emulsifier = 8.31 %; anticorrosive agent = 2.93 %; antioxidant = 0.95 % and biocide = 0.99 %. Computing these variables by substituting them in equation 4.1. The optimized pH value of 10.54 was obtained and confirmation experiment conducted shows a pH value of 10.46.

(b). Cottonseed oil based emulsion cutting fluid.

When the system was optimized for the pH value of oil-in-water emulsion cutting fluid formulated from cottonseed oil based fluid, the most desirable optimal values for the formulation process variables are as follows: emulsifier = 11.81 %; anticorrosion = 3.67 %; antioxidant = 0.76 % and biocide = 0.64 %. Computing these variables by substituting them in equation 4.2. The optimized pH value of 11.00 was obtained and confirmation experiment conducted shows a pH value of 10.98. Thus, it is clear that equations 4.1 and 4.2 are valid for cutting fluid formulation within the limits of the experimental conditions as stated in this report.

4.4.3.1 Viscosity

The viscosities of the formulated cutting fluids for the validated experiment based on the optimal levels for the both palm kernel and cottonseed oils are provided in Table 4.11. Mineral oil based cutting fluid viscosity and pH value were determined after the formulation without optimization process and reported in Table 4.13

Table 4. 11:. Viscosity and pH value of formulated emulsion cutting fluids

Cutting fluid	Optimized pH value	Validated pH value	Viscosity (40^oC) mm^2/s
Palm kernel oil	10.54	10.46	2.97
Cotton seed oil	11.00	10.98	1.04

4.4.3.2 Corrosion level

The corrosion inhibiting ability of the emulsion cutting fluids from the formulated cutting fluid based on the optimal levels were assessed. It was observed that no incidents of corrosion were observed for the two samples of cutting fluids formulated. This is in line with the pH values of all the samples, which is significantly above acidic level. Figure 4.17 shows the filter paper used in the corrosion test for one of the sample tested. It was observed that there was no spot on the filter paper after the experiment.

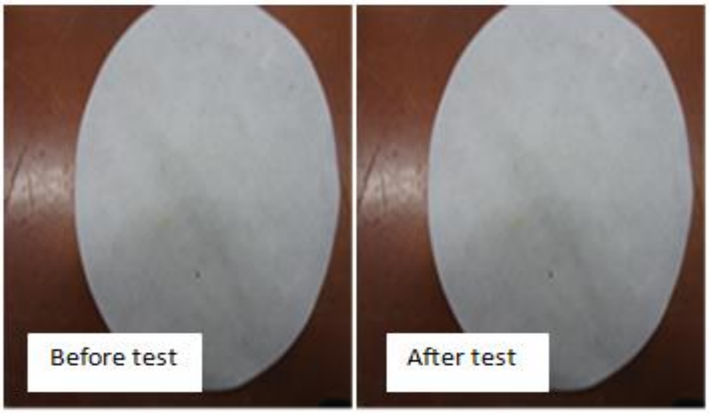


Figure 4.17: Corrosion level test

4.4.3.3 Stability

The stability of the vegetable oil-in-water emulsion cutting fluids was evaluated based on visual transparency within a period of 24 hours at room temperature (25^{o}C) as to phase separation in a graduated 100 mL test tubes. This stability test was carried out for the optimized samples of vegetable oils cutting fluids and mineral oil cutting fluid. The results were reported based on percentage by volume of water that separate from the mixture as shown in Table 4.12.

Table 4.12: Result for stability

Sample	% vol of water
Palm kernel oil cutting fluid	98.0
Cottonseed oil cutting fluid	97.6
Mineral oil cutting fluid	98.0

4.4.3.4 Characteristics of cutting fluids

Table 4.13 show the characteristics of the oil-in-water emulsion cutting fluids formulated. The results for pH value, viscosity, corrosion level, stability and colour of the formulated cutting fluids which involved 10% of oil and 90% of water by volume for the three samples of oils are shown in Table 4.13.

Table 4.13: Characteristics of oil-in-water emulsion cutting fluids

S/N	Property	Value		
		PKO	CSO	MO
1	pH value	10.46	10.98	8.9
2	Viscosity	2.97 mm^2/s	1.04 mm^2/s	0.87 mm^2/s
3	Corrosion level	corrosion resistant	corrosion resistant	7 % corrosion level
4	Stability	stable	stable	stable
5	Colour	whitish	yellowish	milky whitish

4. 5 Turning experiment

Cutting force, surface roughness, tool wear (average flank wear) and chip formation were the parameters evaluated in this study. The Taguchi method L_{27} (3^4) orthogonal array and input parameters selected for the experiment as previously explained in section 3.2.8 was used. A total of 27 experiments based on Taguchi method (L_{27}) orthogonal array were conducted with different combination of levels of the input parameters. The input factors, their levels and responses are shown in Table 4.14. The analysis of the experimental results was subjected to signal to noise (S/N) ratio, ANOVA procedure and comparing the relative performance of the two vegetable oil-based cutting fluids with mineral oil-based cutting fluid. Table 4.15 shows the corresponding S/N (dB) ratio for surface roughness, cutting force and flank wear. The performance of the three cutting fluids were analyzed by Taguchi's "the lower- the better quality" characteristic (S/N ratio) for main cutting force, surface roughness and tool wear. The S/N ratios for the machining force, surface roughness and tool wear were computed using the following equation:

$$\eta = -10\log\left(\frac{1}{n}\sum_{i-1}^{n} y_i^{\ 2}\right) \qquad (4.3)$$

where η is the S/N ratio for the lower-the-better case, y_i the measured quality characteristic for the *ith* repetition, n the number of repetitions in a trial. A statistical analysis software (Minitab-14) widely used in engineering applications was used to study the optimal parameters and the parameters that significantly affect a particular response. While signal-to-noise (S/N) ratio investigates the optimal parameters for a particular response, ANOVA is used to investigate which design parameters significantly affect a particular response and a confidence interval of 95% was specified for the analysis.

Table 4.14: Data from the experimental conducted

Trial No .	Input variables				Output variables		
	Vc (m/min)	Feed (mm/rev)	Doc (mm)	Viscosity η (mm^2/s)	Surface finish (Ra, (µm)	Cutting force (N)	flank wear (VB, mm)
1	160	0.18	1.0	2.97	0.48	508.93	0.072
2	160	0.18	1.0	1.04	0.56	543.76	0.083
3	160	0.18	1.0	0.87	0.88	636.66	0.092
4	160	0.24	1.75	2.97	1.12	563.76	0.088
5	160	0.24	1.75	1.04	1.3	862.41	0.090
6	160	0.24	1.75	0.87	1.42	990.14	0.102
7	160	0.32	3.0	2.97	1.82	767.62	0.078
8	160	0.32	3.0	1.04	2.04	1086.28	0.090
9	160	0.32	3.0	0.87	1.82	1214.00	0.120
10	200	0.18	1.75	2.97	0.4	396.47	0.062
11	200	0.18	1.75	1.04	0.62	715.12	0.077
12	200	0.18	1.75	0.87	0.66	842.85	0.088
13	200	0.24	3.0	2.97	0.81	589.92	0.148
14	200	0.24	3.0	1.04	0.92	908.57	0.161
15	200	0.24	3.0	0.87	1.04	1036.30	0.167
16	200	0.32	1.0	2.97	1.6	340.31	0.141
17	200	0.32	1.0	1.04	1.76	658.96	0.168
18	200	0.32	1.0	0.87	2.08	786.68	0.180
19	250	0.18	3.0	2.97	2.16	563.40	0.204
20	250	0.18	3.0	1.04	2.28	882.05	0.221
21	250	0.18	3.0	0.87	2.34	1009.78	0.247
22	250	0.24	1.0	2.97	2.2	283.37	0.217
23	250	0.24	1.0	1.04	2.48	602.03	0.230
24	250	0.24	1.0	0.87	2.64	729.75	0.237
25	250	0.32	1.75	2.97	3.24	667.26	0.241
26	250	0.32	1.75	1.04	3.4	985.92	0.254
27	250	0.32	1.75	0.87	3.62	1113.64	0.261

Table 4.15: S/N (dB) ratios values for responses

Trial	Surface roughness (μm)	Cutting force (N)	Flank wear (mm)	S/N ratio for surface roughness	S/N ratio for cutting force	S/N ratio for wear
1	0.48	508.9	0.072	6.38	-54.13	22.85
2	0.56	543.8	0.083	5.04	-54.71	21.62
3	0.88	636.7	0.092	1.11	-56.08	20.72
4	1.12	563.8	0.088	-0.98	-55.02	21.11
5	1.3	862.4	0.090	-2.28	-58.71	20.92
6	1.42	990.1	0.102	-3.05	-59.91	19.83
7	1.82	767.6	0.078	-5.20	-57.70	22.16
8	2.04	1086.38	0.090	-6.19	-60.72	20.92
9	1.82	1214.0	0.120	-5.20	-61.68	18.42
10	0.4	396.5	0.062	7.96	-51.96	24.15
11	0.62	715.1	0.077	4.15	-57.09	22.32
12	0.66	842.9	0.088	3.61	-58.52	21.11
13	0.81	589.9	0.148	1.83	-55.42	16.59
14	0.92	908.6	0.161	0.72	-59.17	15.87
15	1.04	1036.3	0.167	-0.34	-60.31	15.53
16	1.6	340.3	0.141	-4.08	-50.64	17.04
17	1.76	658.9	0.168	-4.91	-56.38	15.49
18	2.08	786.7	0.180	-6.36	-57.a92	14.89
19	2.16	563.4	0.204	-6.69	-55.02	13.81
20	2.28	882.1	0.221	-7.16	-58.91	13.11
21	2.34	1009.8	0.247	-7.38	-60.09	12.14
22	2.2	283.4	0.217	-6.85	-49.05	13.26
23	2.48	602.0	0.230	-7.89	-55.59	12.76
24	2.64	729.8	0.237	-8.43	-57.26	12.52
25	3.24	667.3	0.241	-10.21	-56.49	12.35
26	3.4	985.9	0.254	-10.63	-59.88	11.89
27	3.62	1113.6	0.261	-11.17	-60.94	11.68

4.5.1 Cutting force

(a) Signal-to- noise (S/N) ratio analysis

The main effects plots of signal-to-noise ratio (S/N ratio) as shown in Figure 4.18 was used to determine the optimum value for each input parameter during turning process for the cutting force. The lower the better characteristic was chosen for cutting force response. Here, the optimal turning parameters for the main cutting force are 200 m/min of cutting speed (level 2), 0.18 mm/rev of feed (level 1), 1.0 mm of depth of cut (level 1) and 2.97 mm^2/s viscosity of palm kernel oil based cutting fluid (level 3).

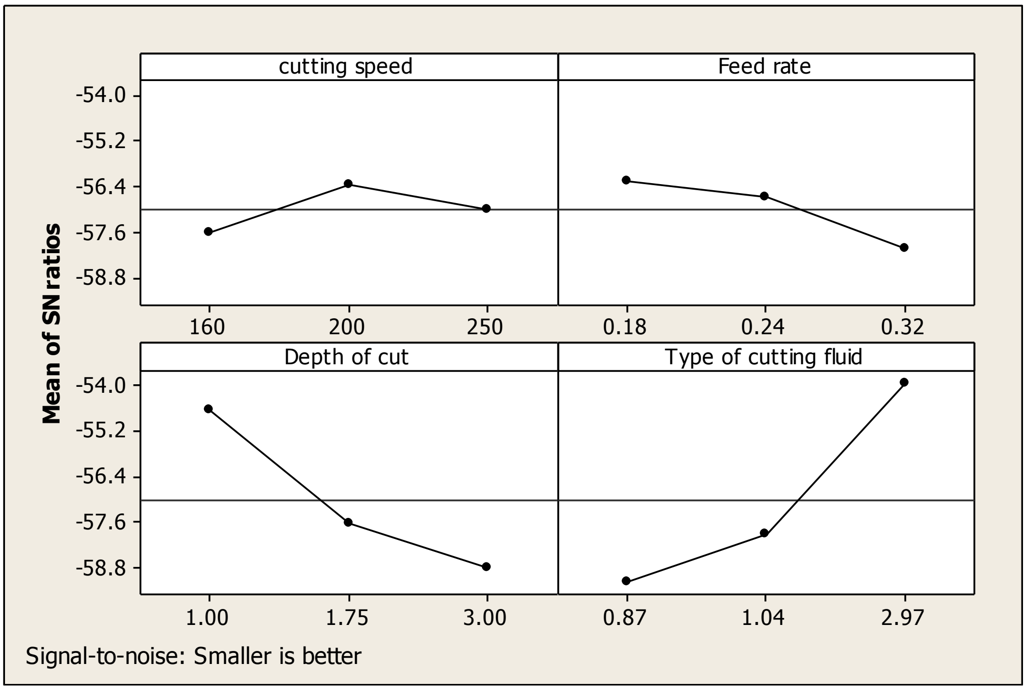


Figure 4.18: Main effect plots of S/N ratio for cutting force

The effectiveness of the formulated cutting fluids in the cutting force reduction followed the following sequence; palm kernel oil-based cutting fluid, cottonseed oil-based cutting fluid and mineral oil-based cutting fluid. Based on the viscosity properties of the oils, this order is expected. The behaviour of different cutting fluids on the main cutting force can be attributed to the fatty acid properties of the oils. The application of lubricant is believed to reduce the friction coefficient at the tool-workpiece interface and hence there is a significant main cutting force reduction. It is believed that a thin boundary film is formed at the tool-workpiece interface. The proportion of saturated fatty acids in PKO is very high, therefore enabling the oil to provide high strength lubricant films that interact strongly with the contact surface despite the small amount of oil in the formulation. This condition helps to reduce both wear and friction. Triglycerides of vegetable oils are known to provide excellent lubricity due to the trigycerol molecule that attaches to the metal surface. This enables the monolayer film formation with the non-polar fatty acids chains, which provides sliding at the contact surface (Yunus et al., 2004). Both vegetable oils in this study show lower cutting force compared with the mineral oil based cutting fluid which is in agreement with Belluco and Chiffre (2004) who reported that the cutting force under vegetable oils was lower than mineral oil.

(b) ANOVA analysis

ANOVA statistics as shown in Table 4.6 was used to study the significance of the input parameters on the cutting force. The significant effects of cutting speed, feed, depth of cut and type of cutting fluids on the cutting force are as follow: cutting speed (2.95%), feed (8.73%), depth of cut (33.15%) and cutting fluids (51.12%). These results show that cutting fluid has more significant impact on the main cutting force, followed by depth of cut. This indicated that cutting fluids and depth of cut are more significant than cutting speed and feed on the cutting force.

Table 4.16: ANOVA analysis for cutting force

Factor	DOF	SS	MS	F	P
Cutting speed (m/min)	2	45781	22890.5	6.601019	0.029599
feed (mm/rev)	2	135019	67509.5	19.46797	0.087295
DOC (mm)	2	512727	256363.5	73.9285	0.331498
Type of cutting fluid (mm^2/s)	2	790749	395374.5	114.0156	0.511251
Error	18	62419	3467.722		0.040356
Total	26	1546695			

Figure 4.19 shows the contour plots of the effects of cutting fluid viscosity (mm^2/s) and depth of cut (mm) on cutting force (N). It was observed that as depth of cut increased with decrease in viscosity of cutting fluid, the cutting force increased.

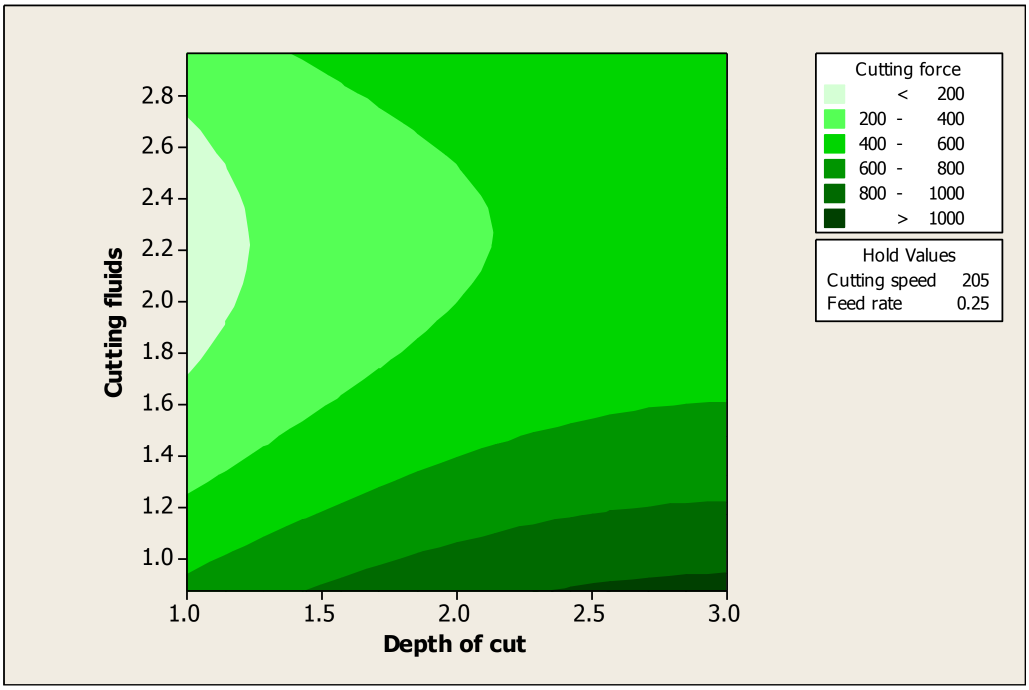


Figure 4.19: Contour plots for cutting force

The 3D surface plot in Figure 4.20 shows the effect of depth of cut and viscosity of cutting fluids on the cutting force. It has a flattened curve shape in line with the model fitted. It is observed that as viscosity of cutting fluid increased with depth of cut, the cutting force decrease which is in agreement with the contour plot.

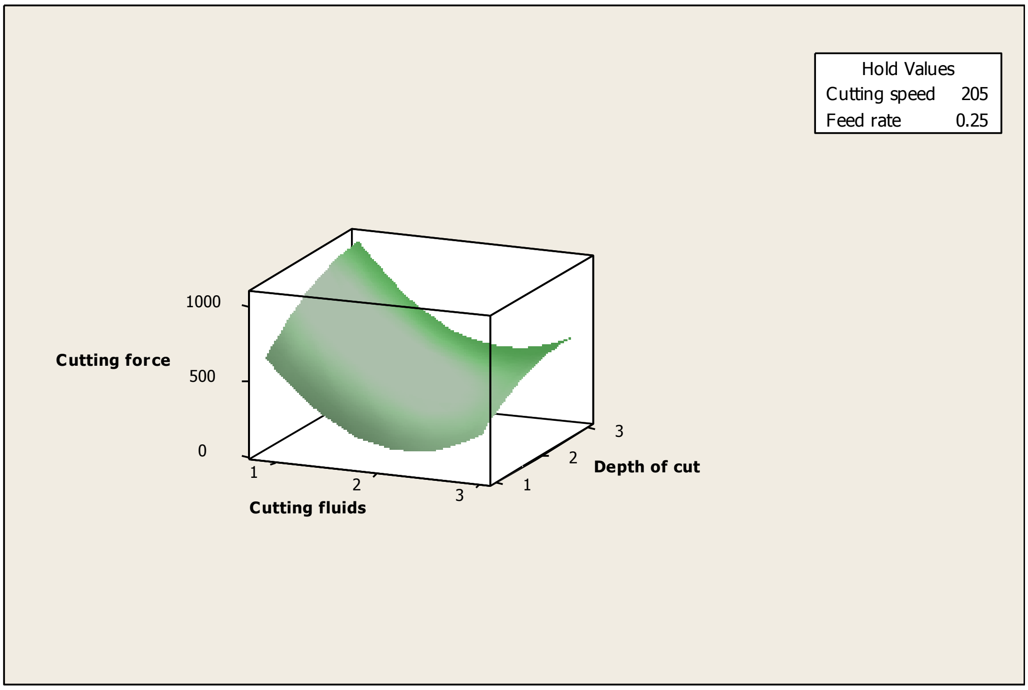


Figure 4.20: 3D surface graph for cutting force

Feed, depth of cut and type of cutting fluids are all significant factors that affect cutting force as shown in Figure 4.21, while Figure 4.22 shows the Pareto chart with the level of contributions of the factors on cutting force.

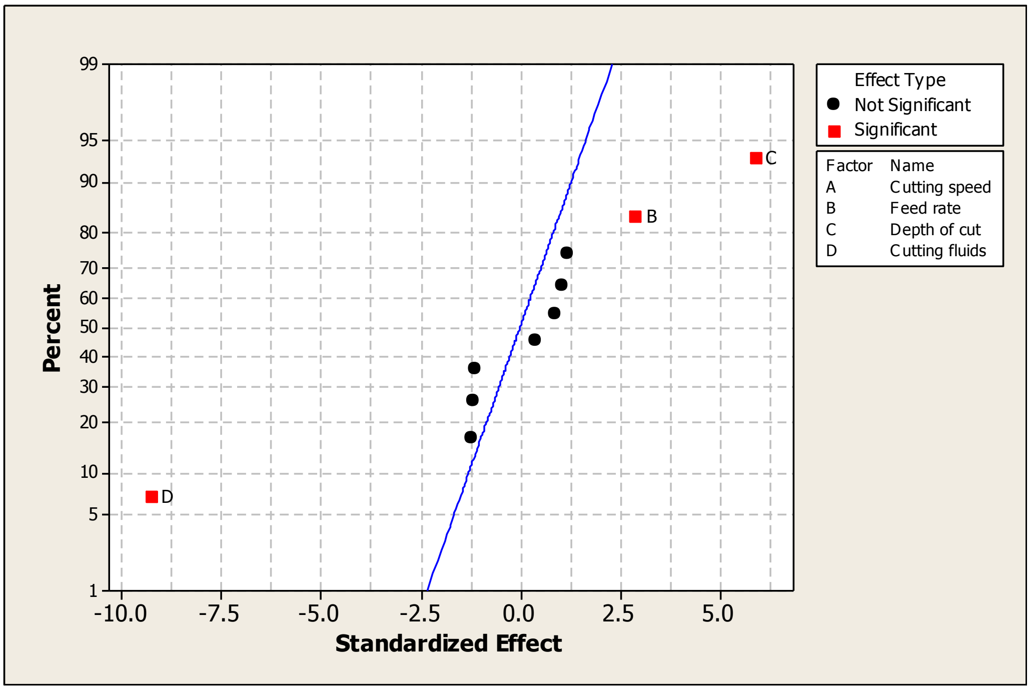


Figure 4.21: Normal probability plot for cutting force

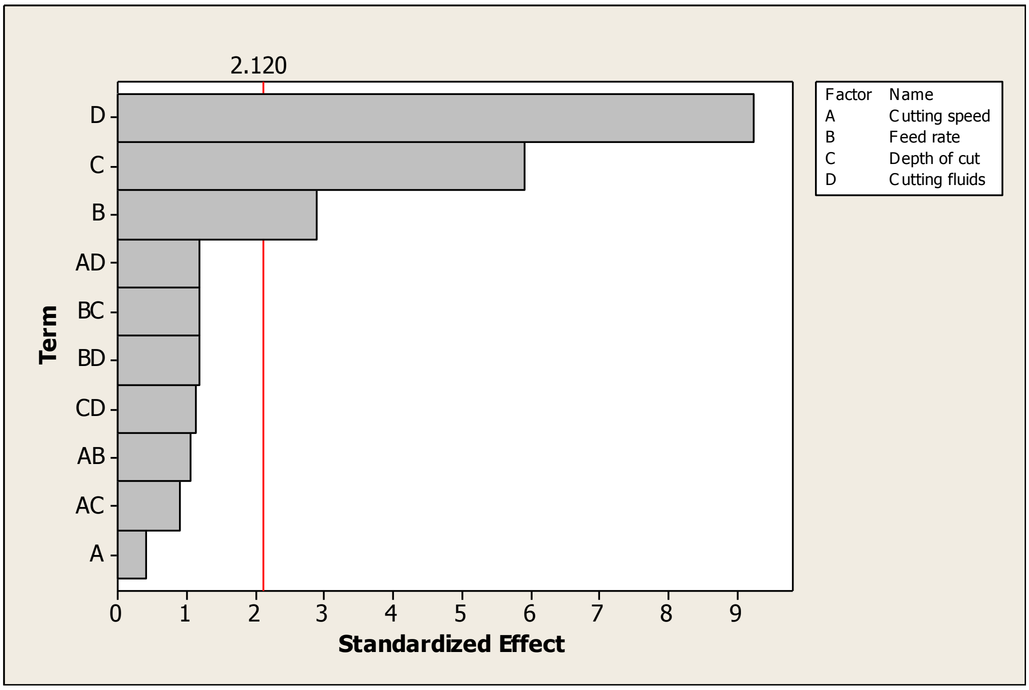


Figure 4.22: Pareto chart for cutting force

(c) Interaction plots for obtained from the output variables

The following general information applies to all the interaction plots obtained for this study. Interaction plots obtained from Taguchi factorial design cannot be used to explain the activities that take place between one factor and the other unlike when full factorial design experimental design (www.taguchisplittest.com/author/admin). This is largely due to the fact all the possible combinations of variables are not normally investigated in Taguchi design. In this study, four variables at three levels (3^4) orthogonal design were studied, it is expected that 81 possible combinations of these four variables at three levels are possible, but applying Taguchi method, 27 selected combinations were investigated. As a result, the interaction plots obtained for output variables (cutting force, surface roughness and flank wear) cannot be used to explain which variable interact and at what point the interact take place, like interaction plots obtain from full factorial experimental design, where all possible combinations of variables are investigated at all levels. This explain the nature of interaction plots obtained for cutting force, surface roughness and flank wear in this study. The interaction plots are produce in this study to show that interaction plot from Taguchi method cannot be used to explain the phenomena of a process.

The interaction plots between the cutting conditions as they affect the cutting force are shown in Figures 4.23. One of the observations in the interaction plots shows that for cutting speed of 160 and 200 m/min, an interaction occurred at 0.24 mm/rev feed. An interaction between cutting speed of 200 and 250 m/min was observed at a point between 0.24 and 0.32 mm/rev feed.

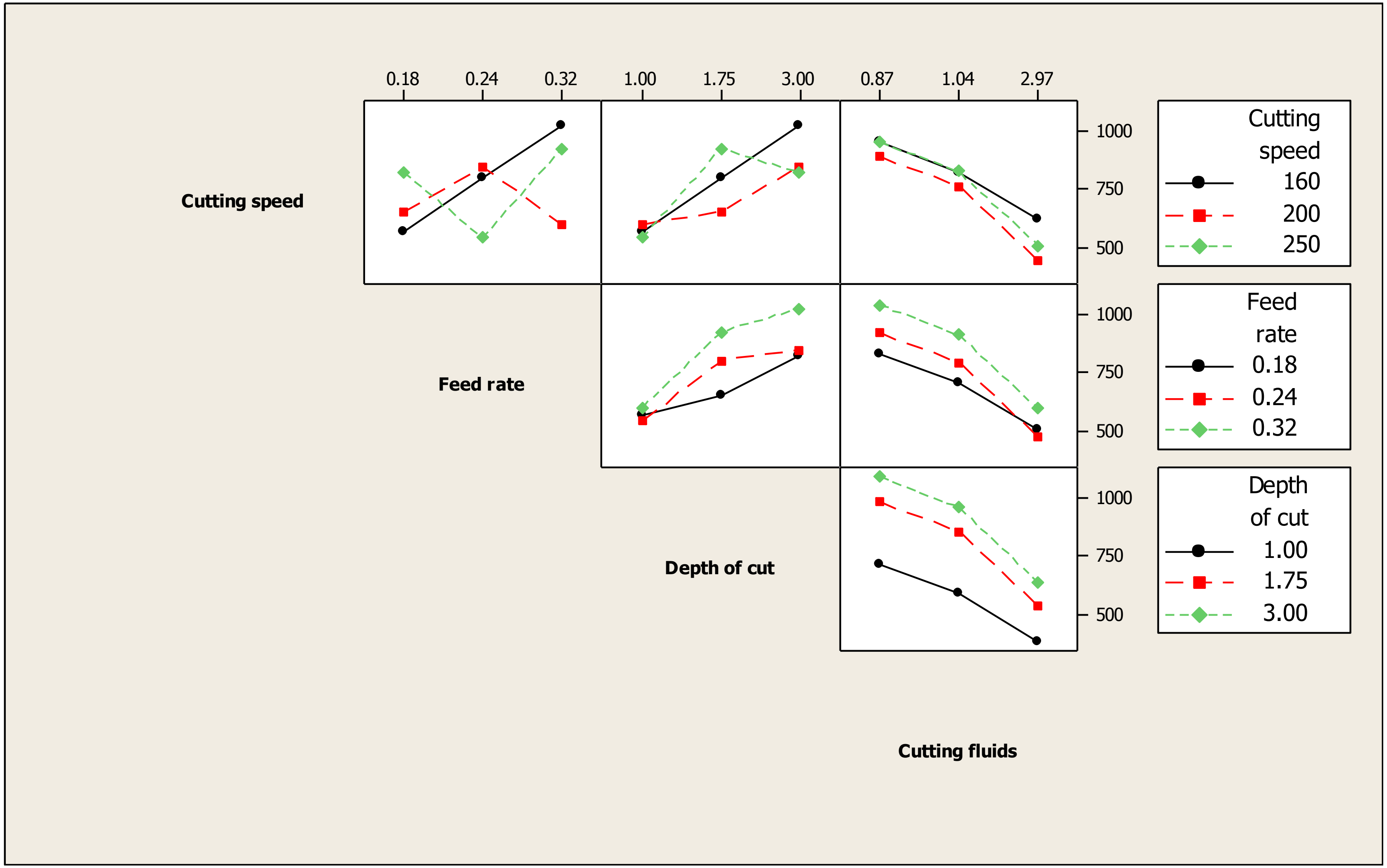


Figure 4.23: Interaction plots for cutting force

However, the interactions between these cutting conditions cannot be used to explain the process that took place during machining because the experimental design is not full factorial.

The effect of cutting fluids under various machining conditions shows that at lower cutting conditions: cutting speed (160 m/min), feed (0.18 mm/rev) and depth of cut (1.0 mm), there is no much difference in the main cutting force for all the cutting fluids. This could be attributed to both the cooling and lubricating properties of the cutting fluids at lower cutting conditions compared with cutting speed (250 m/min), feed (0.32 mm/rev) and depth of cut (1.75 mm) at higher cutting conditions. It was noticed that there was about 20.6% reduction of the cutting force at cutting speed of 160 m/min, feed of 0.18 mm/rev and depth of cut of 1.0 mm machining condition for palm oil based cutting fluid over mineral oil based cutting fluid as shown in appendix B. Also about 14.59% in percentage reduction was observed with cottonseed oil-based cutting under the same machining conditions compared with mineral oil based cutting fluid. At cutting speed of 250 m/min, feed of 0.32 mm/rev and depth of cut of 1.75 mm palm kernel oil based cutting fluid demonstrated about 40.08% reduction in the main cutting force compared with mineral oil based cutting fluid. Under the same cutting conditions, about 11.4% was obtained for the cottonseed oil compared with mineral based oil cutting fluids. This is in agreement with Avila & Abrao (2011) who reported that mineral oils based cutting fluids possess low efficiency at high cutting speeds. The differences in percentage reduction of palm kernel oil based cutting fluid and that of cottonseed oil might be as a result of their fatty acid composition with PKO having a higher saturated fatty acid than CSO. The trend in the reduction was the same for the two vegetable oils compared with the mineral oil as shown in Figures 4.24 to 4.26. From the figures, it is clear between 20 – 56% and 10.52 -17.5% reduction in cutting force was achieved using palm kernel oil and cottonseed oil respectively compared with mineral based oil cutting fluid for all the machining conditions.

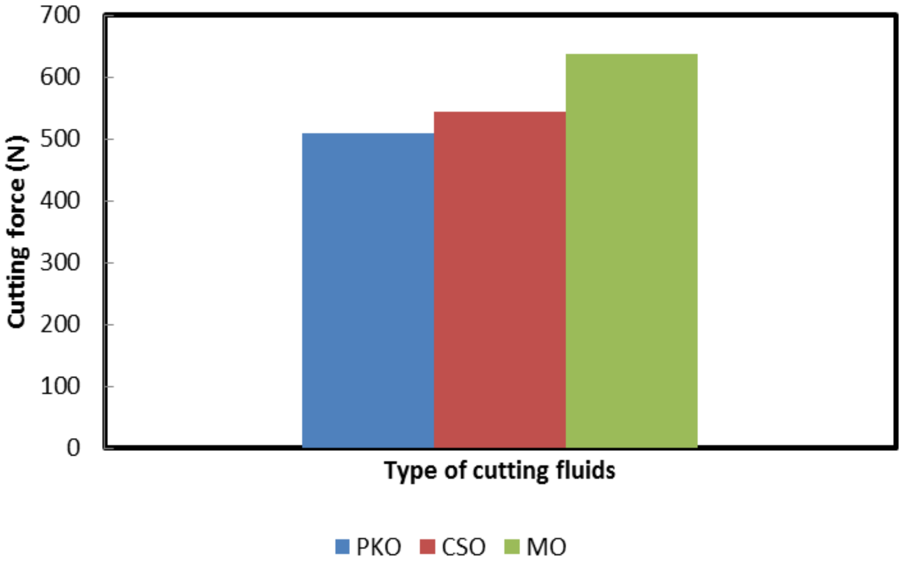


Figure 4.24: Effect of different cutting fluid at cutting speed of 160 m/min, feed of 0.18 mm/rev and depth of cut of 1.0 mm.

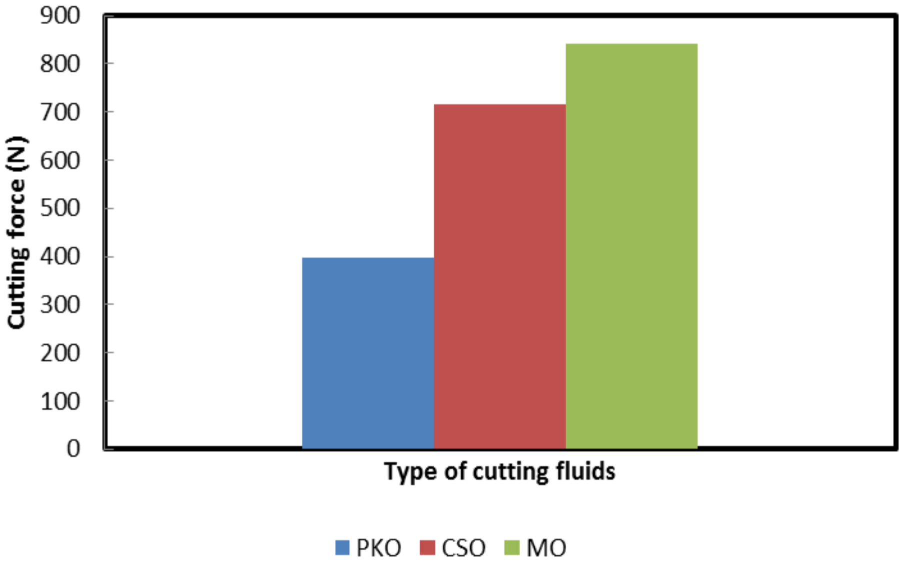


Figure 4.25: Effect of different cutting fluid at cutting speed of 200 m/min, feed of 0.18 mm/rev and depth of cut of 1.75 mm.

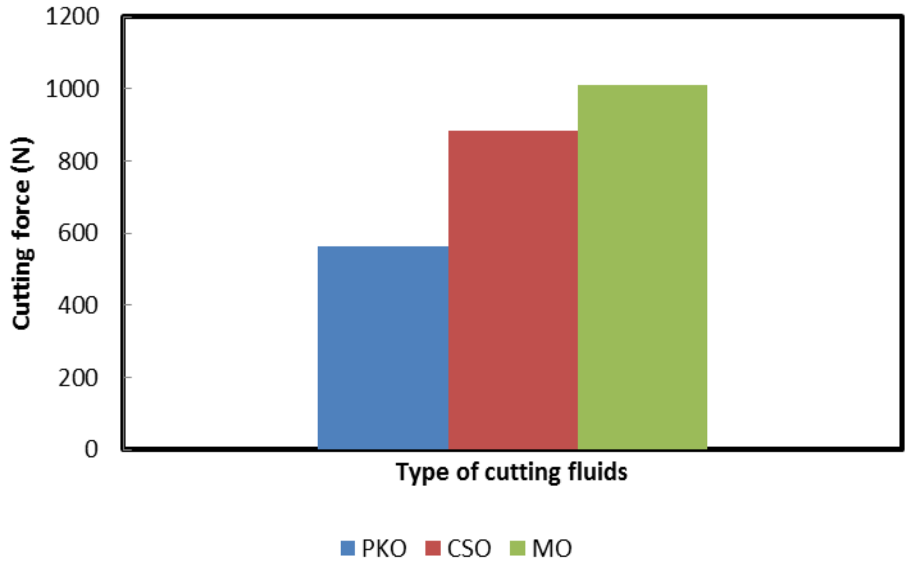


Figure 4.26: Effect of different cutting fluid at cutting speed of 250 m/min, feed of 0.18 mm/rev and depth of cut of 3.0 mm.

4.5.2 Surface roughness

(a) Signal-to-noise (S/N) ration analysis

Three measurements were taken along the shaft axis for each sample and the average value was used for analysis as shown in Table 4.14. Table 4.15 shows the corresponding S/N (dB) ratio for surface roughness. The main effects plot for S/N ratio for surface roughness is shown in Figure 4.27. From the figure, it can be observed that the optimal turning parameters for the surface roughness are 200 m/min of cutting speed (level 2), 0.18 mm/rev of feed (level 1), 1.75 mm of depth of cut (level 2) using palm kernel oil based cutting fluid with viscosity of 2.97 mm^2/s (level 3). Vegetable oil with 2.97 mm^2/s viscosity has more influence on the surface roughness than the other cuttings fluids (cottonseed oil and mineral oil based cutting fluid).

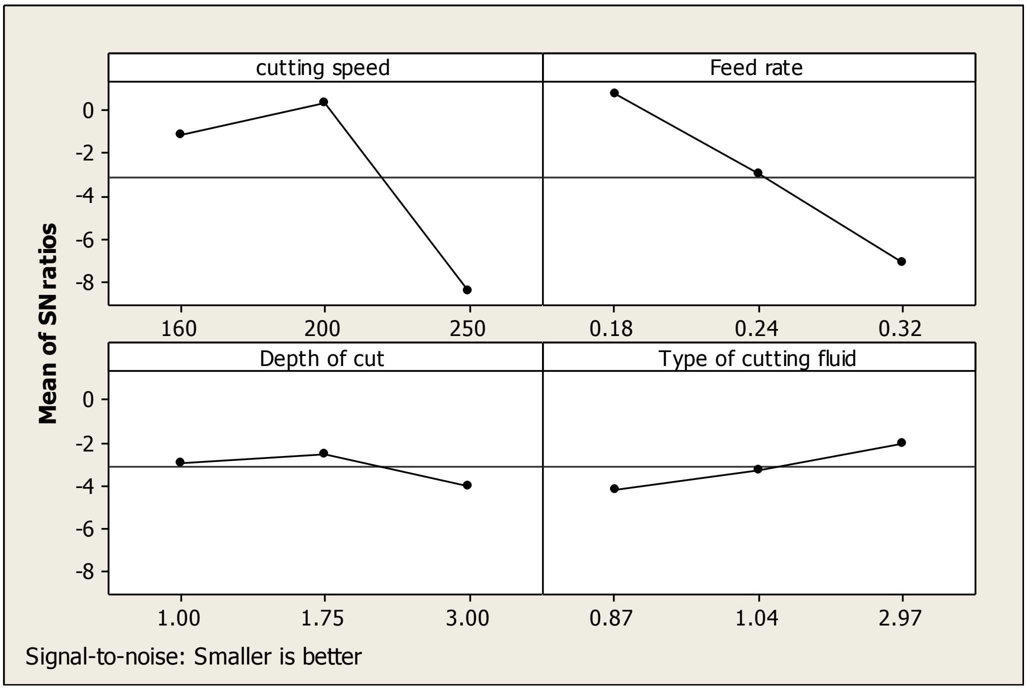


Figure 4.27: Main effects plot for SN ratio for surface roughness

The degree of reduction in the value of the surface roughness by the formulated cutting fluids is in the following sequence: palm kernel oil based cutting fluid, cottonseed oil based cutting fluid and mineral oil based cutting fluid. Again, both lower feed and depth of cut will favour better surface roughness. The different behaviour of vegetable oil based cutting fluids can be explained by the structure of the oils which contain different numbers of fatty acids. The saturated nature of palm kernel oil imparts a strong resistance to oxidative stability in the cutting fluid formulated from it during machining process; This helps in maintaining the cutting fluids properties compared with cottonseed oil which is unsaturated oil (10.41% saturated fatty acid). Noordin *et al.* (2001) observed that surface roughness depends on the feed. Surface roughness values increased with increase in cutting speed and lower feed produced better surface roughness. Higher surface roughness values at higher cutting speeds can be explained by the high ductile nature of AISI 4340 steels, which increases the tendency to form a large and unstable built-up edge (BUE). The presence of the large and unstable BUE causes poor surface finish. Wear at the cutting edge directly influences the machined surface roughness since the edge is in direct contact with the newly machined surface (Ezugwu and Kim, 1995). The results obtained for surface roughness values while machining AISI 4340 steel with coated carbide tools using vegetable oil-based CFs agree with literature (Xavior and Adithan, 2009).

(b) ANOVA analysis

In the same vein, as shown in Table 4.17, ANOVA statistics was used to study the significance of the input parameters on the surface roughness. It is another way of understanding the importance of cutting fluids on surface roughness in this study. The ANOVA result shown in Table 4.17 indicates the contribution of each input parameter (cutting speed, feed, and depth of cut and cutting fluids) as follow: 64.64%, 32.19%, 0.31% and 1.83% respectively. It shows that cutting speed (64.64%) and feed (32.19%) have significant influence on the surface roughness during the machining process.

Table 4. 17: ANOVA analysis for surface roughness

Factor	DF	SS	MS	F	P
Cutting speed (m/min)	2	14.026	0.779222	53.53435	0.644636
Feed (mm/rev)	2	7.004	0.389111	26.73282	0.321905
DOC (mm)	2	0.067	0.003722	0.255725	0.003079
Type of cutting fluid (mm^2/s)	2	0.399	0.022167	1.522901	0.018338
Error	18	0.262	0.014556		0.012042
Total	26	21.758			

Figure 4.28 shows the contour plots for interaction effects of feed and cutting speed on the surface roughness. It is observed that surface roughness increased with increased in feed as cutting speed increased.

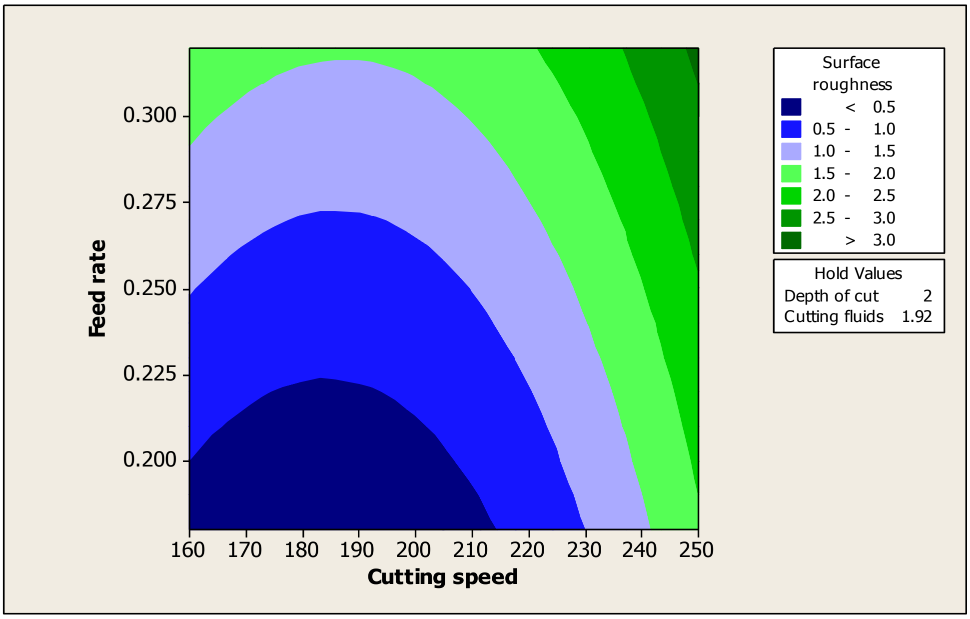


Figure 4.28: Contour plots for surface roughness

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Figure 4.29 shows the 3D graph of the effect of cutting speed and feed on the surface roughness. It is has a curve shape in accordance to the model fitted. It is observed that as cutting speed increased with increase in feed, the surface roughness increased and this is in agreement with the contour plot.

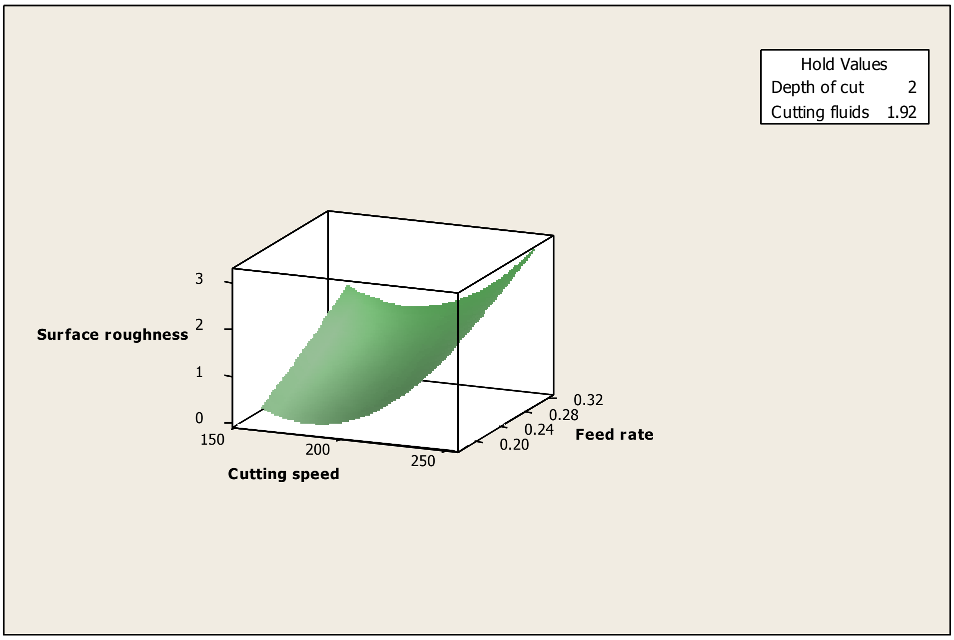


Figure 4.29: 3D surface graph for surface roughness

Figure 4.30 shows all the factors that have significant effect on the surface roughness. From the figure, it is clear that cutting speed and feed have significant effect on the surface roughness as individual factor.

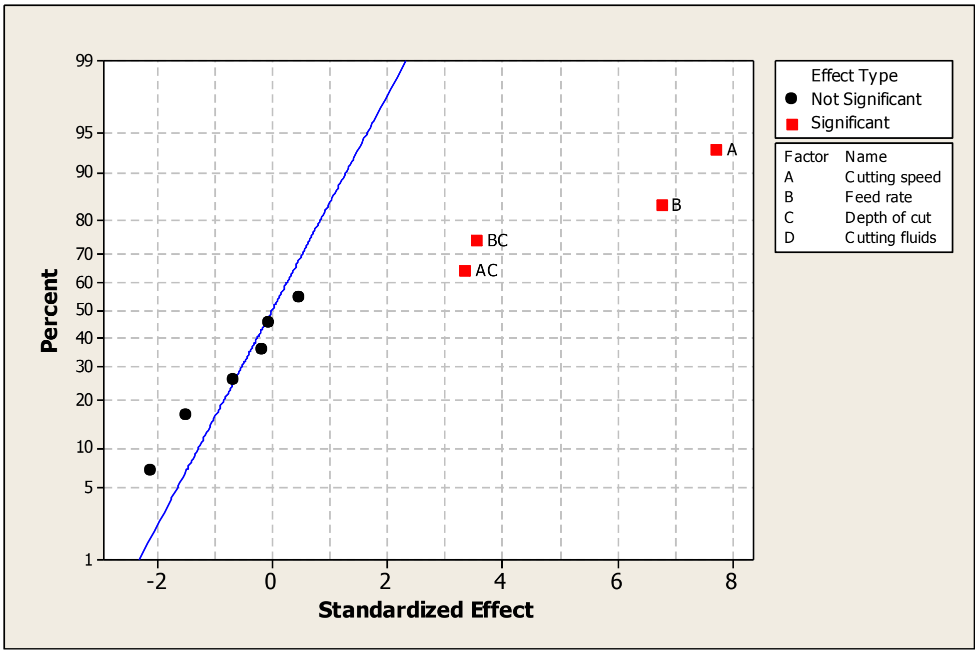


Figure 4.30: Normal probability plot for surface roughness

It can be observed from the normal probability plot that the combinations of feed and depth of cut in one hand and cutting speed and depth of cut on the other hand have significant effect on the surface roughness. While Figure 4.31 shows the Pareto chart which indicate the level of contribution of the factors on surface roughness.

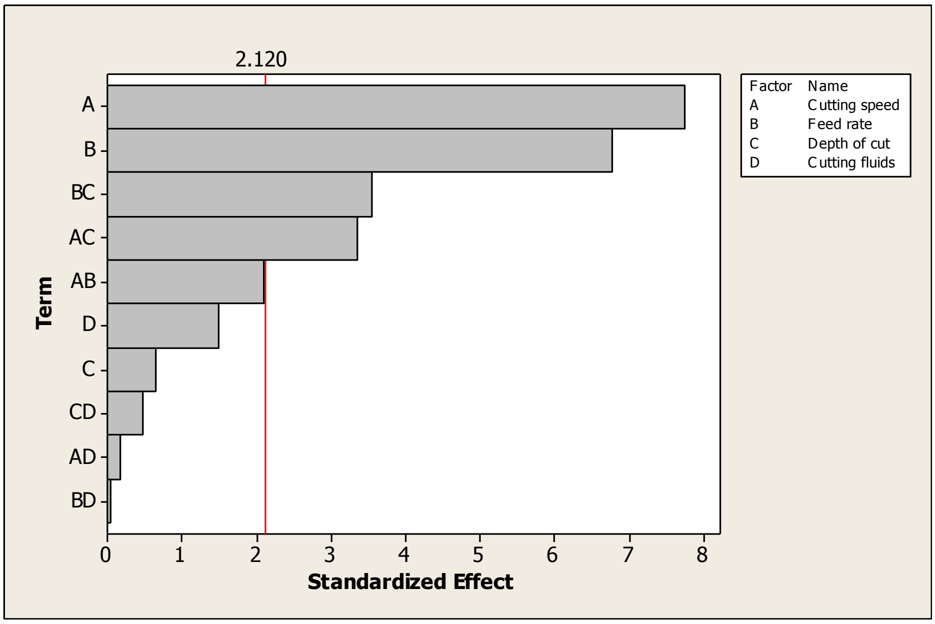


Figure 4.31: Pareto chart for surface roughness.

The interaction plots between the cutting parameters on surface roughness show that there was interaction between cutting speed of 160 and 200 m/min at both feed of 0.18 and 0.32 mm/rev. Within these feeds, there was no any interaction between cutting speed of 250 m/min and other cutting speeds as shown in Figures 4.32. The interaction obtained from these cutting conditions cannot be used to explain the effect of the cutting conditions on surface roughness because it is not a full factorial design experiment.

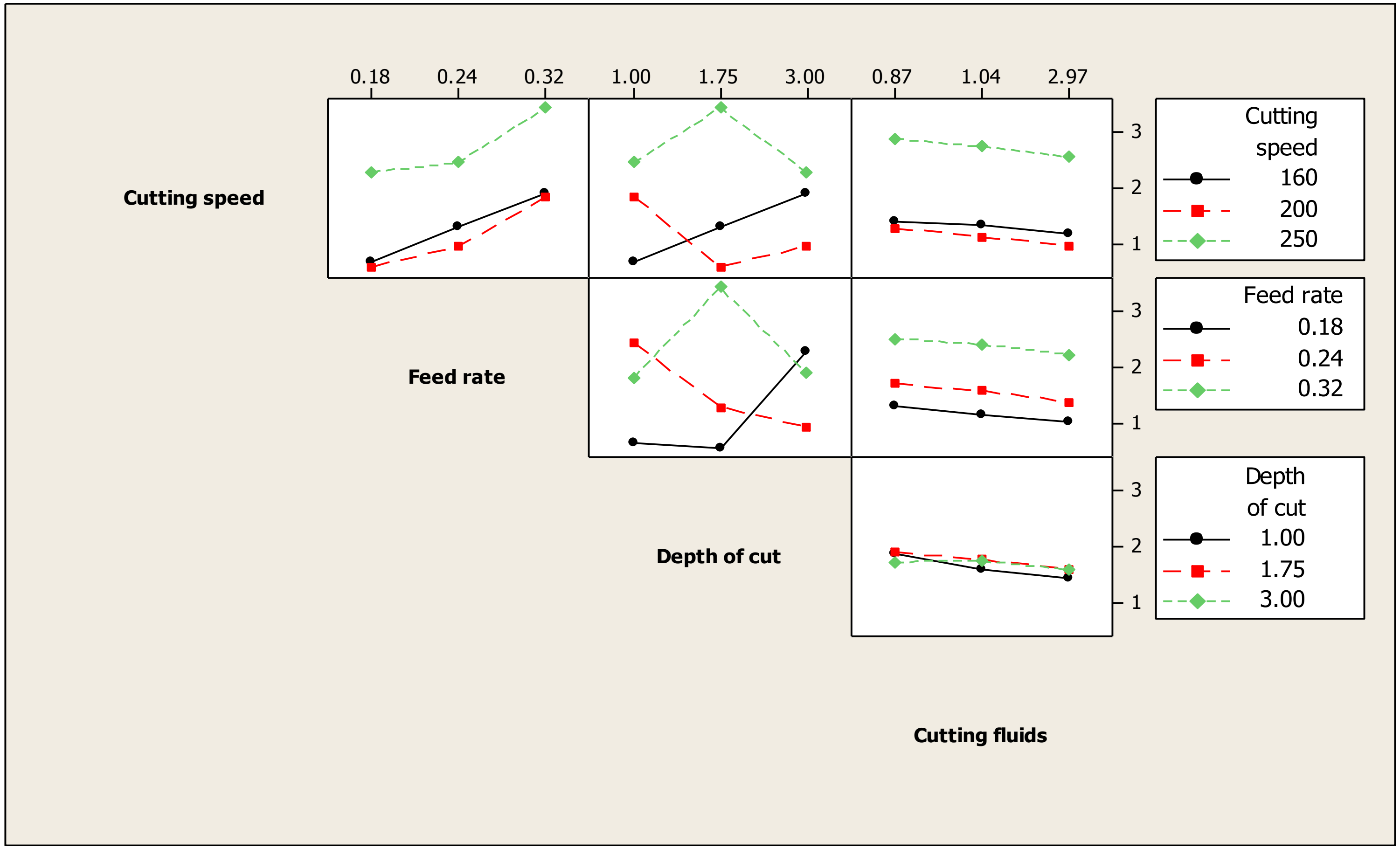


Figure 4.32: Interaction plot for surface roughness

Palm kernel oil based cutting fluid in all cutting conditions show better performance compared with cottonseed oil based cutting fluid and mineral oil based cutting fluid. In the same vein, cottonseed oil-based cutting fluid show better result compared with mineral oil-based cutting fluid as shown in Figures 4.33 to 4.35 for selected cutting conditions and the complete data shown in appendix C. This is in agreement with literature (Belluco and De Chiffre, 2001; Belluco and De Chiffre, 2002; Belluco and De Chiffre, 2004; De Chiffre and Belluco, 2002); Cetin *et al*. 2011).

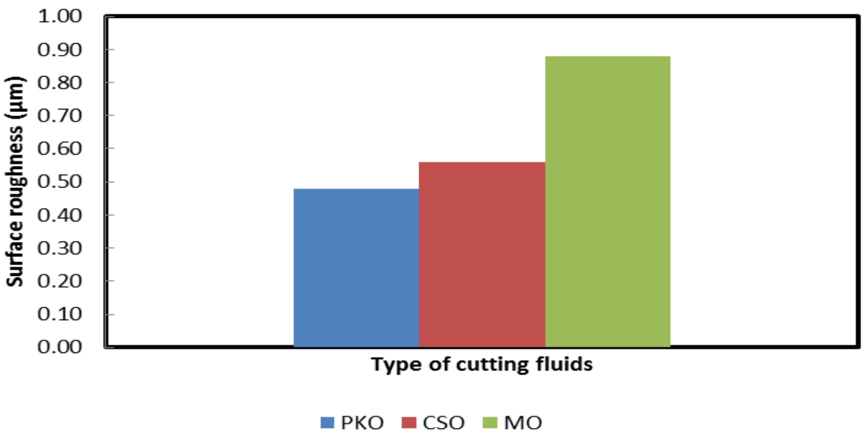


Figure 4.33: Effect of different cutting fluid at cutting speed of cutting speed of 160 m/min, feed of 0.18 mm/rev and depth of cut of 1.0 mm.

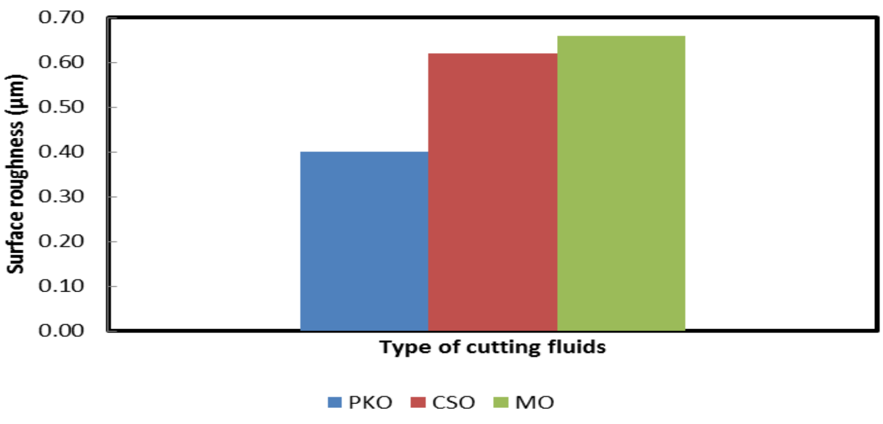


Figure 4.34: Effect of different cutting fluid at cutting speed of 200 m/min, feed of 0.18 mm/rev and depth of cut of 1.75 mm.

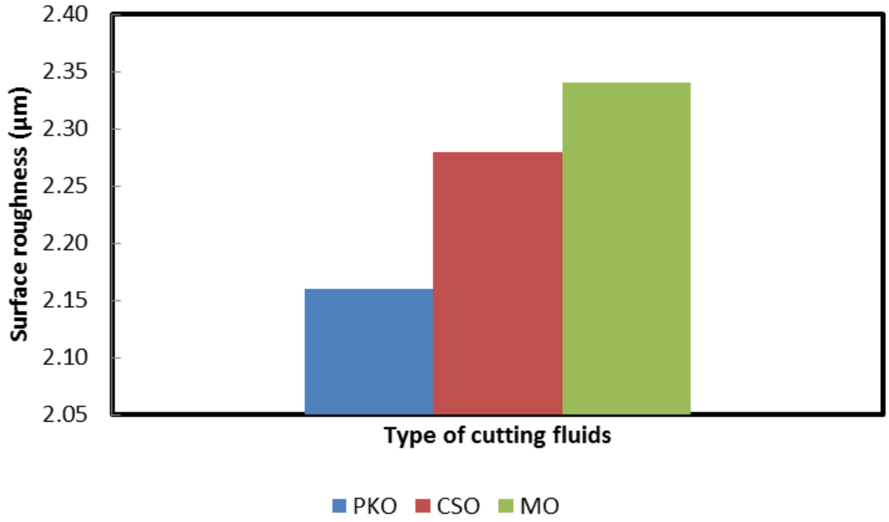


Figure 4.35: Effect of different cutting fluid at cutting speed of 250 m/min, feed of 0.18 mm/rev and depth of cut of 3.0 mm.

4.5.3 Flank wear

(a) Signal-to-noise (S/N) ratio analysis

Figure 4.36 shows the main effects plot for S/N ratio for flank wear. It can be observed from the figure that the optimal turning parameters for the flank wear are 160 m/min of cutting speed (level 1), 0.18 mm/rev of feed (level 1), 1.75 mm of depth of cut (level 2) and 2.97 mm^2/s palm kernel oil based cutting fluid (level 3). It is pertinent to note that palm kernel oil-based cutting fluid exhibited the lowest tool wear than other cutting fluids.

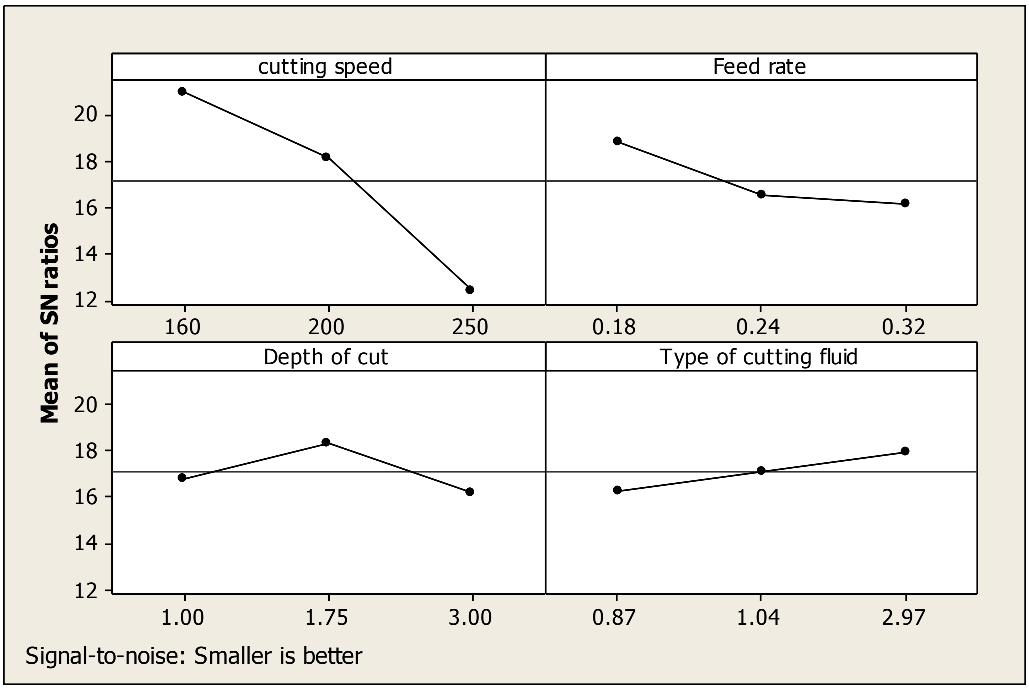


Figure 4.36: Main effect plots of SN ratios for flank wear

This is definitely unconnected with the high saturated fatty acid content in palm kernel oil, which helps significantly to improve reduction friction and wear. Cottonseed oil carbon chain is shorter compare with palm kernel oil. Carbon chain length of fatty acid enhances durability of the contact with material interface. Because of reaction between metal oxide layer and fatty acid, smooth sliding and low friction can be obtained during machining process. In addition, the high viscosity of palm kernel oil-based cutting fluid has the tendency to resist the flow thus provide effective lubrication at the tool-chip interface, which reduces the friction and subsequently prevent the cutting tool from rapid wear.

(b) ANOVA analysis

The ANOVA analysis show that the cutting speed has more significant effect on the flank wear which account for 85.36%; follow by 4.81% of feed , 2.5% of depth of cut and 1.8% of cutting fluids as shown in Table 4.18. It is a known fact that flank wear increase with increased in cutting speed. High speed machining with stainless steel usually result in an extremely high temperature on cutting tools in the cutting zone leading to faster tool wear. Trent (1984) reported that the application of cutting fluid is unable to prevent high temperatures at the tool-chip interface due to the fact that it cannot access the flow zone, where a considerable amount of heat is generated. However, the cooling action can reduce the volume of the tool material that might be damaged by excessive heating.

Table 4.18: ANOVA analysis for flank wear

Factor	DF	SS	MS	F	P
Cutting speed (m/min)	2	0.109657	0.054829	140.5258	0.853628
Feed (mm/rev)	2	0.00619	0.003095	7.932507	0.048186
DOC (mm)	2	0.00322	0.00161	4.126442	0.025066
Type of cutting fluid (mm^2/s)	2	0.00237	0.001185	3.037164	0.018449
Error	18	0.007023	0.00039		0.054671
Total	26	0.12846			

Figure 4.37 shows the contour plots of the effect of cutting speed and feed on flank wear. It is observed that as cutting speed increased with feed the flank wear also increased.

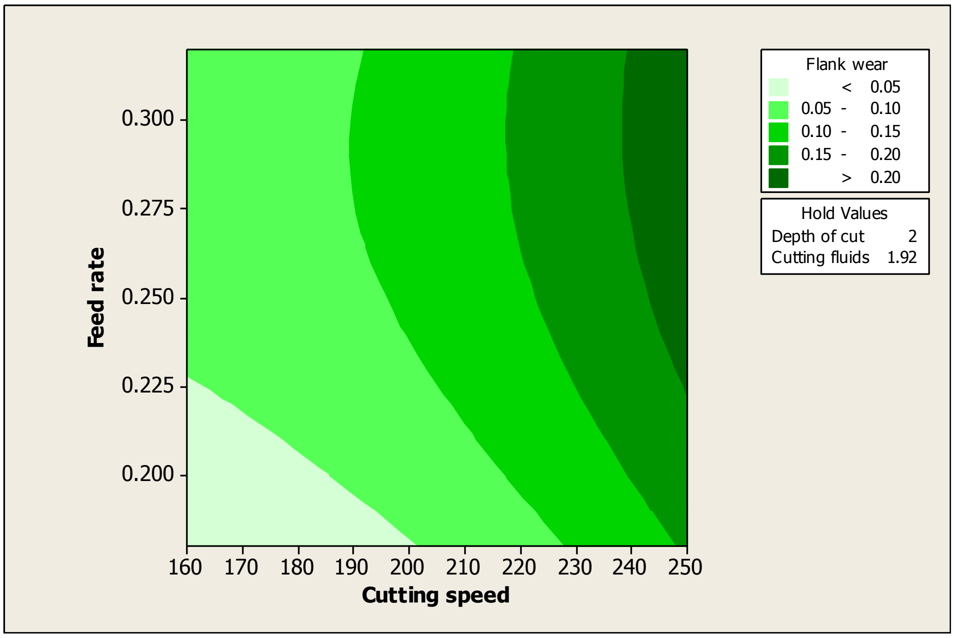


Figure 4.37 : Contour plots for flank wear

Figure 4. 38 shows the 3D graph of the effect of feed and cutting speed on the flank wear of the tool. The curve shape obtained is in accordance to the model fitted and in agreement with the contour plot. Flank wear increase as cutting speed increased with increase in feed.

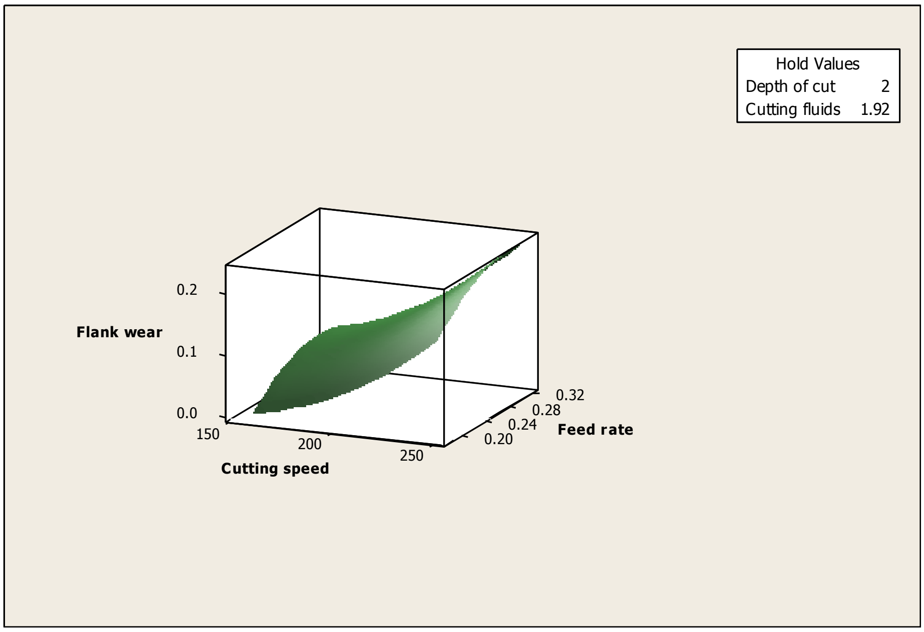


Figure 4.38: 3D surface graph for flank wear

The normal probability plot in Figure 4.39 shows that both cutting speed and feed are significant factors that affect the flank wear and the combination of cutting speed and depth of cut are equally significant factors that affect flank wear..

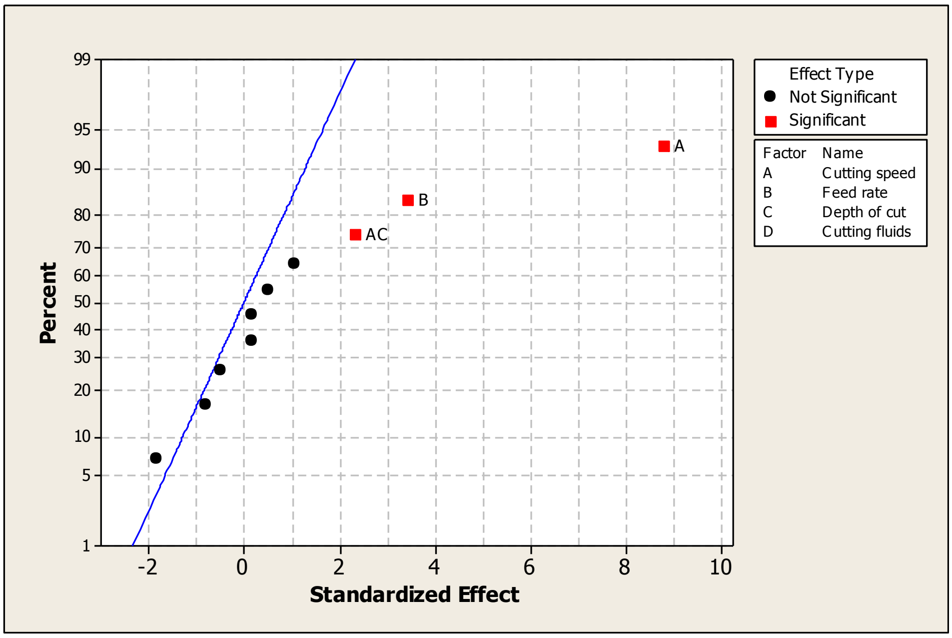


Figure 4.39: Normal probability plot for flank wear

Fig. 4.40 shows the Pareto chart as it affects the contribution level of each factor to flank wear.

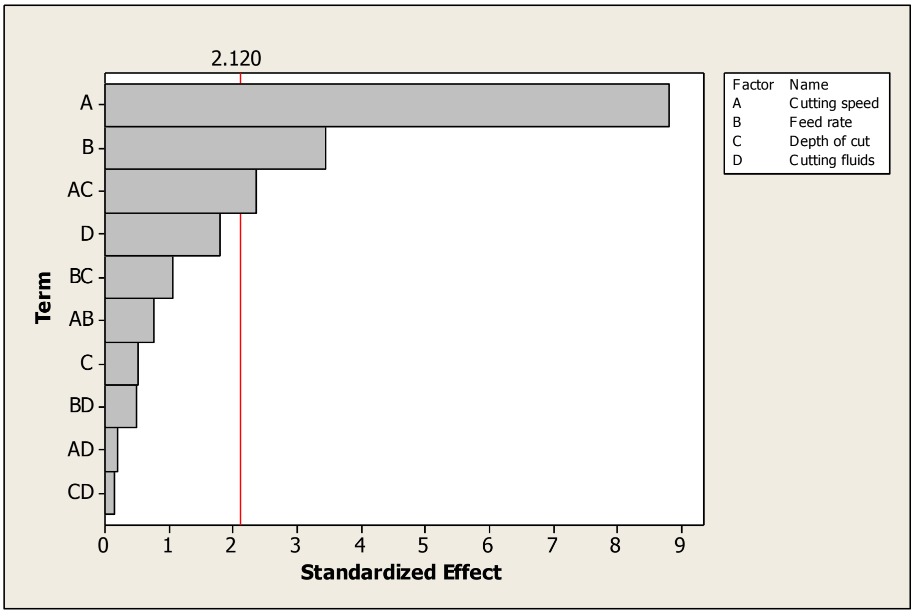


Figure 4.40: Pareto chart for flank wear

The interaction plots between the cutting parameters on flank wear are shown in Figures 4.41. It was observed that as feed increases from 0.18 to 0.32 mm/rev, there was interaction between cutting speed of 160 and 250 m/min at 0.18 m/rev feed. However, there was no interaction between cutting speed of 250 m/min with other cutting speeds within the same range of feed. All other interaction plots of the cutting variables cannot be used to explain the effect of these cutting variables on the flank wear because it is not a full factorial design.

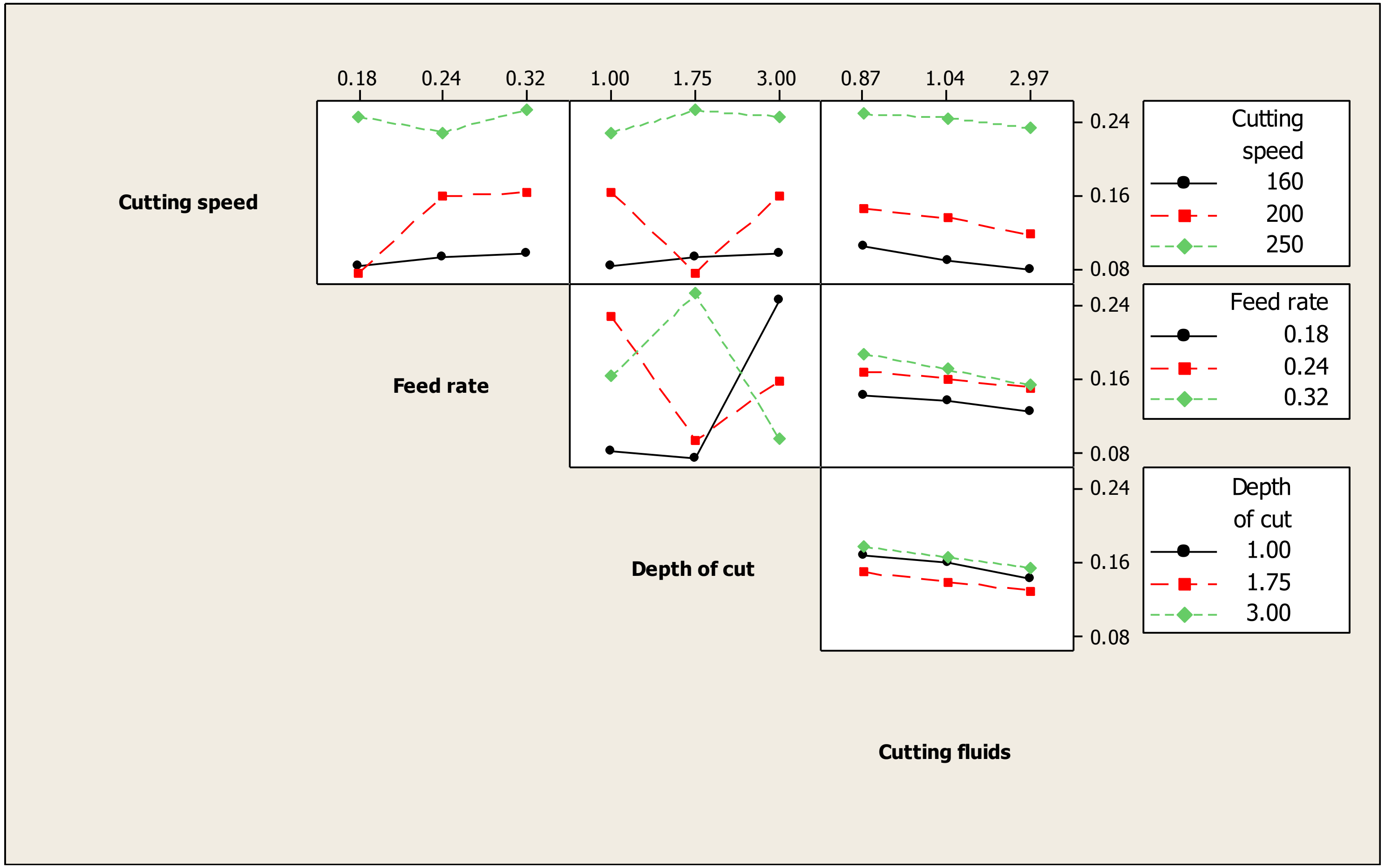


Figure 4.41: Interaction plot for flank wear

Figures 4.42 to 4.44 depict the effect of various cutting fluids on the flank wear and it generally show that both vegetable oils based cutting fluids improved the flank wear compared with the mineral oil based cutting fluid. Appendix D shows that palm kernel oil based cutting fluid in all cutting conditions show better performance compared with cottonseed oil based cutting fluid and mineral oil based cutting fluid. In the same vein, cottonseed oil-based cutting fluid show better result compared with mineral oil-based cutting fluid. This is in agreement with literature (Belluco and De Chiffre, 2001; Belluco and De Chiffre, 2002; Belluco and De Chiffre, 2004; De Chiffre and Belluco, 2002); Cetin *et*. *al*., 2011).

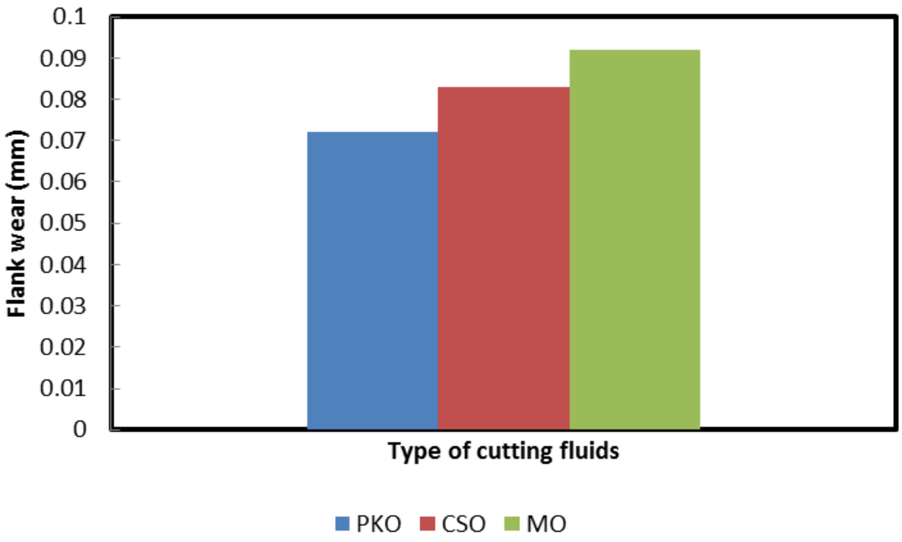


Figure 4.42: Effect of different cutting fluid at cutting speed of 160 m/min, feed of 0.18 mm/rev and depth of cut of 1.0 mm

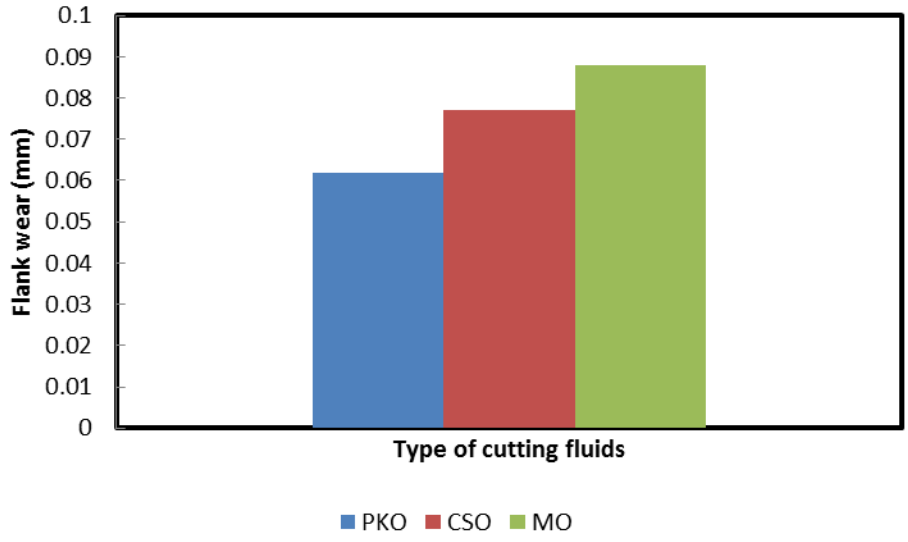


Figure 4.43: Effect of different cutting fluid at cutting speed of 200 m/min, feed of 0.18 mm/rev and depth of cut of 1.75 mm.

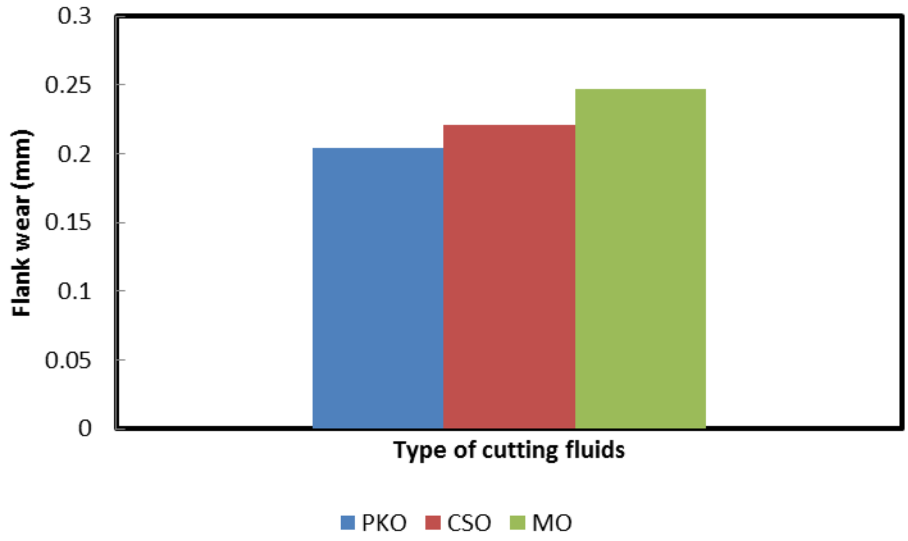


Figure 4.44: Effect of different cutting fluid at cutting speed of 250 m/min, feed of 0.18 mm/rev and depth of cut of 3.0 mm.

Figure 4.45 represents the flank wear pictures taken at various cutting conditions at 50× magnification. While Figure 4.46 represents the flank wear pictures taken at cutting speed of 250 m/min, feed of 0.18 mm/rev and depth of cut of 3.0 mm under the three cutting fluids environment at 200 × magnification.

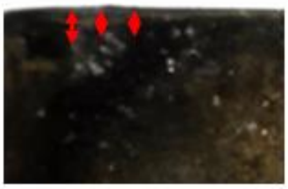
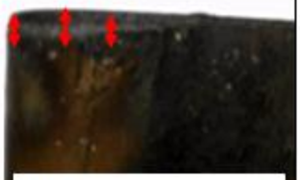
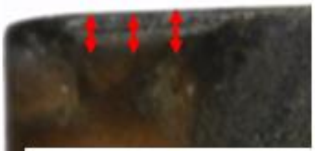
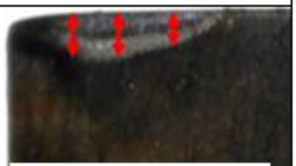
Cutting conditions	PKO	CSO	MO
Vc = 160 m/min f = 0.18 mm/rev doc = 1.0 mm	 $V_{B_{av}}$ = 0.072 mm	 $V_{B_{av}}$ = 0.083 mm	 $V_{B_{av}}$ = 0.092 mm
Vc = 250 m/min f = 0.18 mm/rev doc = 3.0 mm	 $V_{B_{av}}$ = 0.204 mm	 $V_{B_{av}}$ = 0.221 mm	 $V_{B_{av}}$ = 0.247 mm

Figure 4.45: Flank wear at 50× magnification.

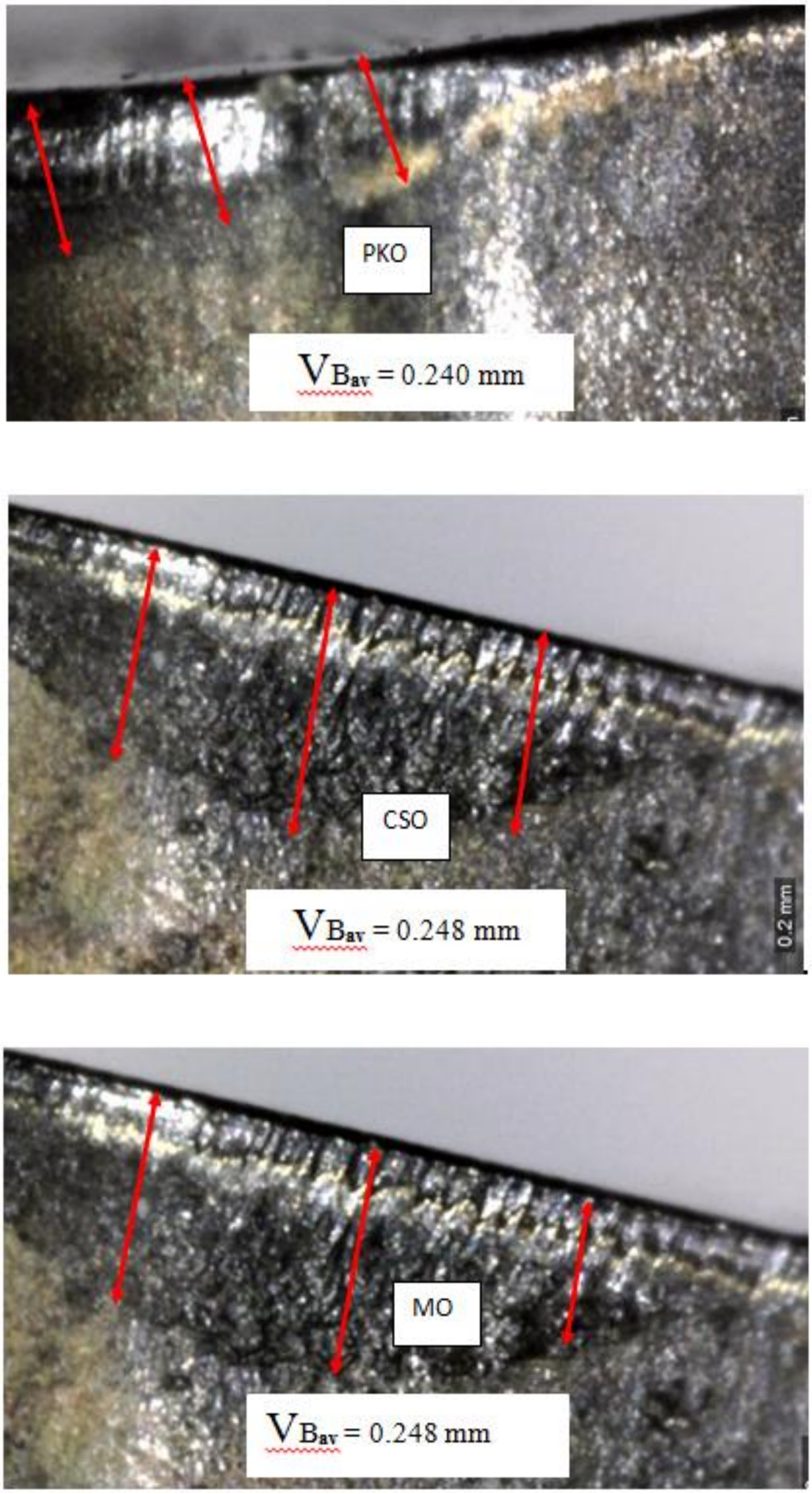


Figure 4.46: Flank wear at 200 × magnification

4.5.4 Confirmation test

Mathematical models for cutting parameters such as cutting speed, feed, depth of cut and cutting fluids were obtained from regression analysis using MINITAB 14 software to predict cutting force, surface roughness and flank wear. The following notations were used in the mathematical models V_c: cutting speed, *f:* feed, a_p: depth of cut, CF: cutting fluid, V_B: Flank wear, *Ra*: surface roughness and F_c: cutting force.

The optimal value obtained from the ANOVA results for cutting force surface roughness and flank wear are shown in the Table 4.19. These optimized values were used to determine the predicted value using regression equations 4.5 – 4.7. The summary of calculated and experimental results are shown in Table 4.20

Table 4.19: Optimal values for various output parameters

Parameter	Cutting force	Surface roughness	Flank wear
Cutting speed (m/min)	200	200	160
Feed (mm/rev)	0.18	0.18	0.18
Depth of cut (mm)	1.0	1.75	1.75
Viscosity (mm^2/s)	2.97	2.97	2.97

(a) the cutting force (F_r) model equation obtained is as follows:

$$F_r = 497 - 0.323V_C + 1223f + 157a_p - 173CF \quad (4.5)$$

when V_c = 200 m/min, f = 0.18 mm/rev, a_p = 1.0 mm and CF = 2.97 mm^2/s

F_c = 295.73 N

R^2 = 85.1% and R^2 (adj) = 82.4%

(b) the surface roughness (Ra) model equation obtained is as follows:

$$R_a = -3.71 + 0.0166V_c + 8.82f + 0.022a_p - 0.119CF \qquad (4.4)$$

when V_c = 200 m/min, f = 0.18 mm/rev, a_p = 1.75 mm and CF = 2.97 mm^2/s

R_a = 0.883 µm

R^2 = 79.8% and R^2 (adj) = 76.1%

(c) the flank wear (VB) model equation obtained is as follows:

$$V_B = -0.249 + 0.00170V_c + 0.250f + 0.00608a_p - 0.00913CF \qquad (4.6)$$

when V_c = 160 m/min, f = 0.18 mm/rev, a_p = 1.75 mm and CF = 2.97 mm^2/s

V_B= 0.0515 mm

R^2 = 88.8% and R^2 (adj) = 86.8%

Table 4.20: Confirmation test percentage error

Parameter	calculated value	experimental value	Percentage error (%)
Surface roughness	0.883 µm	0.921 µm	4.13
Cutting force	295.73 N	285 .83 N	3.35
Flank wear	0.0515 mm	0.0485 mm	5.82

All the values of R^2 obtained from cutting force, surface roughness and flank wear are in agreement with regression models. In any multiple linear regression analysis, R^2 is a value of correlation coefficient and should be between 0.8 and 1.0 (Montgomery et al., 1998).

4.5.5 Chip formation

Chips formation during machining process can be classified into (i) continuous, (ii) built-up edge (iii) serrated or segmented and (iv) discontinuous. The identification of different types of chips formed during turning process of AISI 4340 steel with coated carbide tools were assessed in term of classification above under different cutting fluid environments. The chips were collected randomly at different cutting conditions for analysis. In the present investigation which was done under various cutting conditions during turning of AISI 4340 steel with coated carbide tool; it was observed that in all the cases, at low cutting speed and low depth of cut, long cyclic arc type, thin chips were produced. When cutting speed was increased from 160 m/min to 200 m/min continuous cyclic steady state were observed. Similarly, when cutting speed was increased from 200 m/min to 250 m/min with low feed and depth of cut, serrated, steady state and large curvature chips were produced. Continous, cyclic / sprial type chips except in some cases where slight distortion of chip was noticed under the cutting conditions of cutting speed (160.0 m/min), feed (0.18 mm/rev) and depth of cut (1.0 mm).

Cutting conditions	PKO	CSO	MO
(a) *Vc* = 160 m/min *f* = 0.18 mm/rev *d* = 1.0 mm			
(b) *Vc* = 160 m/min *f* = 0.32 mm/rev *d* = 3.0 mm			
(c) *Vc* = 200 m/min *f* = 0.24 mm/rev *d* = 3.0 mm			
(d) *Vc* = 200 m/min *f* = 0.32 mm/rev *d* = 1.0 mm			
(e) *Vc* = 250 m/min *f* = 0.18 mm/rev *d* = 3.0 mm			
(f) *Vc* = 250 m/min *f* = 0.32 mm/rev *d* = 1.75 mm			

Figure 4.47: Type of chip formation

The continuous chips at above conditions are probably due to effective machining because of shearing of workpiece leading to plastic deformation. However, larger curvature was noticed for mineral based cutting fluid as shown in Figure 4.47(a). A continuous steady state chip formation with was observed at cutting speed (160 m/min), feed (0.32 mm/rev) and depth of cut (3.0 mm) as shown in Figure 4.47(b). The size of curvature depends on the depth of cut during turning process. The colour of chips form at this stage was brownish.

The types chips formed at cutting speed (200 m/min), feed (0.24 mm/rev) and depth of cut (3.0 m) and cutting speed (200 m/min), feed (0.32 mm/rev) and depth of cut (1.0 m) changed appreeciably into a very long continous steady state in shapes with some having wavy curls as shown in Figure 4.47 (c and d). For cutting condition of cutting speed (250 m/min), feed (0.18 mm/rev) and depth of cut (3.0 m), a continous chips formation with large curvature and black colour were observed as shown in Figure 4.47(e). This type of chip formation must have been due to high temperature generated at these cutting conditions. While a combination of staedy state and a very long continous chip formation with large curvature were observed at cutting speed (250 m/min), feed (0.32 mm/rev) and depth of cut (1.75 m) as shown in Figure 4.47(f).

The cutting conditions for (a), (b) and (e) is highly recommended for turning AISI 4340 steel with coated carbide especially if the output consideration is surface roughness. The chip formed during these cutting conditions were removed from the cutting zone easily and this prevented the chip formed from scratching the workpiece.

CHAPTER 5

5 Conclusion and recommendations

5.1 Conclusions

In this study, the effect of vegetable and mineral oil-in-water emulsion cutting fluids in turning AISI 4340 steel with coated carbide has been exploited. The study can be classified into two basic sections. The first section dealt with formulation and characterization of cutting fluids from palm kernel oil and cottonseed oil. Details properties of these oils were investigated as it affects their uses as cutting fluid. Effect of antioxidant on the oxidative and thermal stabilities of the two oils was investigated using TGA. Similarly, DSC was used to study the low temperature property of the oils. Design of experiment (DOE) full factorial method was used to formulate the cutting fluid with water to oil ratio of 9:1 and four different additives. The performance of these cutting fluids were assessed using Taguchi method through the evaluation of turning parameters on surface roughness, cutting force, flank wear and chip formation. Findings from a comparative study of these emulsion cutting fluids are hereby summarized in this chapter. Also some recommendations on future work have been made.

1. The results of fatty acid composition for the two samples of oil shows that palm kernel oil has an approximately 69.95% saturated fat with the main contributors being 44.06% lauric acid, 16.17% myristic acid and 9.52% palmitic acid. While 20.96% of palm kernel oil is unsaturated fatty acid with 17.91% oleic acid (monounsaturated) and 3.05% linoleic acid (polyunsaturated). Cottonseed oil has approximately 10.43% saturated fat with the main contributor being 0.10% myristic acid and 10.31% palmitic acid. While about 80.01% is unsaturated with 29.24% oleic acid (monounsaturated) and 50.77% linoleic acid

(polyunsaturated). The different in the fatty acid composition of these vegetable oils affected their performances as cutting fluid in turning AISI 4340 steel with coated carbide tools.

2. An onset temperature of degradation of 275^{o}C was observed for all the samples in oxygen environment and a significant weight gain of 38% at 300^{o}C was notice for all the samples for PKO. While, the onset temperature for all the samples in oxygen environment was observed to have taken place at 207^{o}C, but there is a significant weight gain in the temperature range between 207 and 550^{o}C for CSO.

3. The onset temperature of decomposition for both PKO and CSO are lower under oxygen environment, but there was weight gain between temperature ranges of 180 - 500^{O}C due to formation of oxidation products. The weight gain for PKO at approximately 300^{o}C is around 25% compared with weight gain by CSO at 450^{o}C which is about 18%.

4. When the system was optimized for the pH value of oil-in-water emuslion cutting fluid formulated from palm kernel oil, the desirable optimal values for the formulation process variables are as follows: emulsifier = 8.31%; anticorrosive agent = 2.93%; antioxidant = 0.95% and biocide = 0.99%.
5. When the system was optimized for the pH value of oil-in-water emulsion cutting fluid formulated from cottonseed oil, the desirable optimal values for the formulation process variables are as follows: emulsifier = 11.81%; anticorrosion = 3.67%; antioxidant = 0.76% and biocide = 0.64%.
6. The viscosities of the validated optimized vegetable oil cutting fluid and that of mineral oil based cutting fluid were determined to be 2.97; 1.04 and 0.87 mm^2/s for PKO, CSO and MO respectively.

7. The optimal turning parameters for the surface roughness are 200 m/min of cutting speed (level 2), 0.18 mm/rev of feed (level 1), 1.75 mm of depth of cut (level 2) and palm kernel oil based cutting fluid with viscosity of 2.97 mm^2/s (level 3).
8. The ANOVA analysis show the contribution of each input parameter such as cutting speed, feed, and depth of cut and cutting fluids as follow: 64.64%, 32.19%, 0.31% and 1.83% respectively for surface roughness.
9. The optimal turning parameters for the main cutting force are 200 m/min of cutting speed (level 2), 0.18 mm/rev of feed (level 1), 1.0 mm of depth of cut (level 1) and 2.97 mm^2/s viscosity of palm kernel oil based cutting fluid (level 3).
10. ANOVA analysis was used to study the significant of the input parameters on the cutting force. The significant effects of cutting speed, feed, depth of cut and cutting fluids on the cutting force are as follow: cutting speed (2.95%), feed (8.73%), depth of cut (33.15%) and cutting fluids (51.12%).
11. the optimal turning parameters for the tool wear are 160 m/min of cutting speed (level 1), 0.18 mm/rev of feed (level 1), 1.75 mm of depth of cut (level 2) and 2.97 mm^2/s palm kernel oil based cutting fluid (level 3).
12. The ANOVA analysis show that the cutting speed has more significant effect on the tool wear with cutting speed (85.36%) follow by feed (4.81%), depth of cut (2.5%) and cutting fluids (1.8%)
13. The multiple regression analysis indicates the fitness of experimental measurements. Regression models obtained from the surface roughness (R^2 = 79.8%), cutting force (R^2 = 85.1%) and flank wear (R^2 = 88.8%) measurements match well with the experimental data.

14. The confirmation tests carried out using regression equations show reliable results as the percentage error was between 3.35 and 5.82 for the three output variables
15. This experimental study shows that PKO and CSO based cutting fluids could be used in machining process and thereby reduce occupational health risks, lower costs towards waste treatment due to their higher biodegradability and better performance rate.

5.2 Recommendation for future work

Further investigation to develop these cutting fluids for variety of applications on machining processes such as milling, grinding and drilling on different types of metals with various cutting tools, will help machining industries to access environmentally friendly cutting fluids.

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List of publications

Papers published

1 **S.A. Lawal**, I.A. Choudhury, Y. Nukman , *Developments in the Formulation and application of vegetable oil-based metalworking Fluids in Turning Process*, International Journal of Advanced Manufacturing Technology. DOI:10.1007/s00170-012-4607-0

2 **Sunday Albert Lawal,** Imtiaz Ahmed Choudhury, Yusoff Nukman, (2013), *A Critical Assessment of Lubrication Techniques in Machining Processes: A Case for Minimum Quantity Lubrication Using Vegetable Oil- Based Lubricant,* Journal of Cleaner Production, 41, 210 -221

3 **S.A. Lawal**, I.A. Choudhury, Y. Nukman (2012), *Application of vegetable oil-based metalworking fluids in machining ferrous metals –A review*; International Journal of Machine Tools and Manufacture, 52, 1-12

4 **Sunday Albert Lawal,** Imtiaz Ahmed Choudhury, Yusoff Nukman, An Assessment of the Physico-chemical Properties of Melon Seed (Citrullus lanatus) Oil as Based Material for Oil-in-Water Emulsion Cutting Fluid, Advanced Materials Research, vol. 576 (2012) pp 293 -295.

5 **Sunday Albert Lawal,** Imtiaz Ahmed Choudhury, Yusoff Nukman *"Evaluation of vegetable and mineral oil-in-water emulsion cutting fluids in turning AISI 4340 steel with coated carbide tools"* Journal of Cleaner Production**,(Revise submission)**

6 **Sunday Albert Lawal,** Imtiaz Ahmed Choudhury, Yusoff Nukman*," Evaluation of palm kernel oil as base oil for metalworking fluid*" Industrial Crops and Production: An international Journal (**under review**)

Conference

1. **Sunday A. Lawal,** Imtiaz A. Choudhury, Mohammed B. Ndaliman , Yusoff Nukman, "*Formulation of Sustainable Eco-Friendly Cutting Fluid for Machining Process Using Statistical Method"* presented at 3rd Biennial Engineering Conference, Federal University of Technology, Minna- Nigeria. 14th -16th May, 2013

2. **Sunday Albert Lawal,** Imtiaz Ahmed Choudhury, Yusoff Nukman, "An Assessment of the Physico-chemical Properties of Melon Seed (Citrullus lanatus) Oil as Base Material for Oil-in-Water Emulsion Cutting Fluid", presented at International Conference on Advances in Manufacturing and Materials Engineering, 3rd - 5th July, 2012. Kuala Lumpur, Malaysia

Appendices

Appendix A

Table A1: Chromatography data

S/N	Palm kernel oil		Cottonseed oil	
	Time	Count	Time	Count
1	4.331	0	4.331	0
2	5.793	14890.03	5.801	0
3	7.235	235948	7.225	703.4827
4	8.514	241940	8.502	408.4636
5	9.134	3056.104	9.146	0
6	9.896	3634960	9.8	5730.976
7	10.536	4449.936	10.549	0
8	11.424	1333950	11.347	6666.321
9	11.775	0	11.775	0
10	12.276	1148.49	12.274	1006.234
11	12.769	0	12.769	0
12	13.396	785693	13.389	676359
13	13.718	1560.198	13.716	7218.911
14	14.487	1796.721	14.491	5177.134
15	14.864	383.2345	14.865	3251.65
16	15.853	212506	15.586	1623.759
17	16.014	0	15.918	238669
18	16.27	1477450	16.31	1679310
19	16.432	261.5427	16.36	76843.9
20	16.879	251952	17.057	3253290
21	17.296	7517.776	17.434	24028.8
22	17.713	8749.862	17.814	508341
23	18.533	11704.4	18.541	197550.3
24	18.941	10073.8	18.953	14284
25	19.762	0	19.721	1907.529
26	19.995	0	20.005	1460.9
27	20.239	0	20.239	0
28	20.553	0	20.553	0
29	20.959	0	20.959	0
30	21.278	594.9741	21.47	0
31	21.573	2933.316	21.593	19587.9
32	22.091	0	22.04	888.8782
33	23.122	509.502	23.13	716.9324
34	23.376	1052.437	23.399	2684.638
35	24.572	0	24.598	1818.264
36	25.459	4331.116	25.462	6414.252

Appendix B

Table A2: Cutting force percentage reduction

Trial	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Type of cutting fluid (mm^2/s)	Cutting force (N)	% improvement
1	160	0.18	1	2.97	508.93	20.06
2	160	0.18	1	1.04	543.76	14.59
3	160	0.18	1	0.87	636.66	
4	160	0.24	1.75	2.97	563.76	43.06
5	160	0.24	1.75	1.04	862.41	12.89
6	160	0.24	1.75	0.87	990.14	
7	160	0.32	3	2.97	767.62	36.76
8	160	0.32	3	1.04	1086.28	10.52
9	160	0.32	3	0.87	1214.00	
10	200	0.18	1.75	2.97	396.47	52.96
11	200	0.18	1.75	1.04	715.12	15.15
12	200	0.18	1.75	0.87	842.85	
13	200	0.24	3	2.97	589.92	43.07
14	200	0.24	3	1.04	908.57	12.33
15	200	0.24	3	0.87	1036.30	
16	200	0.32	1	2.97	340.31	56.74
17	200	0.32	1	1.04	658.96	16.24
18	200	0.32	1	0.87	786.68	
19	250	0.18	3	2.97	563.40	44. 20
20	250	0.18	3	1.04	882.05	12.65
21	250	0.18	3	0.87	1009.78	
22	250	0.24	1	2.97	283.37	61.17
23	250	0.24	1	1.04	602.03	17.50
24	250	0.24	1	0.87	729.75	
25	250	0.32	1.75	2.97	667.26	40. 08
26	250	0.32	1.75	1.04	985.92	11.47
27	250	0.32	1.75	0.87	1113.64	

Appendix C

Table A3: Surface roughness percentage reduction

Trial	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Type of cutting fluid (mm^2/s)	Surface roughness (µm)	% improvement
1	160	0.18	1	2.97	0.48	14.29
2	160	0.18	1	1.04	0.56	36.36
3	160	0.18	1	0.87	0.88	
4	160	0.24	1.75	2.97	1.12	13.85
5	160	0.24	1.75	1.04	1.30	8.45
6	160	0.24	1.75	0.87	1.42	
7	160	0.32	3	2.97	1.82	10.78
8	160	0.32	3	1.04	2.04	-
9	160	0.32	3	0.87	1.82	
10	200	0.18	1.75	2.97	0.40	35.48
11	200	0.18	1.75	1.04	0.62	6.06
12	200	0.18	1.75	0.87	0.66	
13	200	0.24	3	2.97	0.81	11.95
14	200	0.24	3	1.04	0.92	11.54
15	200	0.24	3	0.87	1.04	
16	200	0.32	1	2.97	1.60	9.09
17	200	0.32	1	1.04	1.76	15.38
18	200	0.32	1	0.87	2.08	
19	250	0.18	3	2.97	2.16	5.26
20	250	0.18	3	1.04	2.28	2.56
21	250	0.18	3	0.87	2.34	
22	250	0.24	1	2.97	2.20	11.29
23	250	0.24	1	1.04	2.48	6.06
24	250	0.24	1	0.87	2.64	
25	250	0.32	1.75	2.97	3.24	4.70
26	250	0.32	1.75	1.04	3.40	6.08
27	250	0.32	1.75	0.87	3.62	

Appendix D

Table A4: Flank wears percentage reduction

Trial	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Type of cutting fluid (mm^2/s)	Tool wear (N)	% improvement
1	160	0.18	1	2.97	0.072	21.73
2	160	0.18	1	1.04	0.083	9.78
3	160	0.18	1	0.87	0.092	
4	160	0.24	1.75	2.97	0.088	13.7
5	160	0.24	1.75	1.04	0.090	11.76
6	160	0.24	1.75	0.87	0.102	
7	160	0.32	3	2.97	0.078	35.0
8	160	0.32	3	1.04	0.090	25.0
9	160	0.32	3	0.87	0.120	
10	200	0.18	1.75	2.97	0.062	29.54
11	200	0.18	1.75	1.04	0.077	12.95
12	200	0.18	1.75	0.87	0.088	
13	200	0.24	3	2.97	0.148	11.49
14	200	0.24	3	1.04	0.161	3.81
15	200	0.24	3	0.87	0.167	
16	200	0.32	1	2.97	0.141	21.91
17	200	0.32	1	1.04	0.168	6.7
18	200	0.32	1	0.87	0.180	
19	250	0.18	3	2.97	0.204	17.45
20	250	0.18	3	1.04	0.221	10.56
21	250	0.18	3	0.87	0.247	
22	250	0.24	1	2.97	0.217	8.12
23	250	0.24	1	1.04	0.230	2.69
24	250	0.24	1	0.87	0.237	
25	250	0.32	1.75	2.97	0.241	7.37
26	250	0.32	1.75	1.04	0.254	2.45
27	250	0.32	1.75	0.87	0.261	