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Application of vegetable oil-based metalworking fluids in machining ferrous metals—A review

S.A. Lawal^{a,b,*}, I.A. Choudhury^a, Y. Nukman^a^a Department of Engineering Design and Manufacture, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia^b Department of Mechanical Engineering, School of Engineering and Engineering Technology, Federal University of Technology, 920001 Minna, Nigeria

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ABSTRACT

The increasing attention to the environmental and health impacts of industrial activities by governmental regulations and by the growing awareness level in the society is forcing industrialists to reduce the use of mineral oil-based metalworking fluids as cutting fluid. Cutting fluids have been used extensively in metal cutting operations for the last 200 years. In the beginning, cutting fluids consisted of simple oils applied with brushes to lubricate and cool the machine tool. As cutting operations became more severe, cutting fluid formulations became more complex. There are now several types of cutting fluids in the market and the most common types can be broadly categorized as cutting oils or water-miscible fluids. In this review, the applicability of vegetable oil-based metalworking fluids in machining of ferrous metals has been undertaken. The advantages of metalworking fluids and its performances with respect to the cutting force, surface finish of work piece, tool wear and temperature at the cutting zone have been investigated. It has been reported in various literature that metalworking fluids, which are vegetable oil-based, could be an environmentally friendly mode of machining with similar performance obtained using mineral oil-based metalworking fluids.

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1. Introduction

Metalworking fluids (MWFs) are one of the types of lubricants, which are extensively used in machining operations. There are

several types of MWFs which may be used to carry out such tasks [1]. Most of the MWFs are mineral oil-based fluids and these fluids increase productivity and the quality of manufacturing operations by cooling and lubricating during metal cutting and forming processes [2]. Due to their advantages, the consumption of MWFs is increasing in machining industry. It is reported that the European Union alone consumes approximately 320,000 tonnes per year of MWFs out of which at least two-thirds need to be disposed [3]. Despite their widespread use, they pose significant

* Corresponding author at: Department of Engineering Design and Manufacture, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia. Tel.: +60105346120, +2348036578168.

E-mail address: lawalbert2003@yahoo.com (S.A. Lawal).

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 [4–8]. Estimation shows that in the USA alone about 700,000 to one million workers are exposed to MWFs [9]. As cutting fluids are complex in their composition, they may cause irritation or allergy. Microbial toxins are also generated by bacteria and fungi present, particularly in water-soluble cutting fluids [10], and they are very harmful to the operators. To overcome these challenges, various alternatives to petroleum-based MWFs 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 [11,12], most especially in machining operations. The public awareness in environmental issues has been constantly growing [13]. 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 [14]. Vegetable oils, especially rapeseed [15] and canola [16] are some of the more promising candidates as basestocks for the biodegradable lubricants. They are readily biodegradable and less costly than synthetic basestocks. They often show quite acceptable performance as lubricants [17]. Cutting fluids are normally classified into three main groups; that is; (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, as shown in Fig. 1. Fluids within these classes are available for light, medium and heavy duty performance [18].

In general, vegetable oils are highly attractive substitutes for petroleum-based oils because they are environmentally friendly, renewable, less toxic and readily biodegradable [19,20]. Consequently, vegetable-based oils are more potential candidates for use in industry as lubricants/MWFs. Many investigations are in progress to develop new bio-based cutting fluids from various vegetable oils available around the world. Because of environmental concerns and growing regulations over contamination and pollution, the increase in need for renewable and biodegradable lubricants is highly expected. An annual growth rate of 7–10% for environmentally favourable lubricants is expected in the US market over the next few years compared to a rate of only 2% for the overall lubricant market [21]. Vegetable oils are a viable and

renewable source of environmentally friendly oils. The majority of vegetable oils consist primarily of triacylglycerides, 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 [22,23]. Fig. 2 shows a typical chemical structure of triglyceride of vegetable oil, where R_1 , R_2 and R_3 are long chains of carbons and hydrogen atoms, sometimes called fatty acid chains.

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

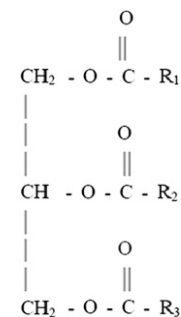


Fig. 2. Chemical structure of triglyceride of a typical vegetable oil [24].

Table 1
Advantages and disadvantages of vegetable oils as lubricants [36].

Advantages	Disadvantages
High biodegradability	Low thermal stability
Low pollution of the environment	Oxidative stability
Compatibility with additives	High freezing points
Low production cost	Poor corrosion protection
Wide production possibilities	
Low toxicity	
High flash points	

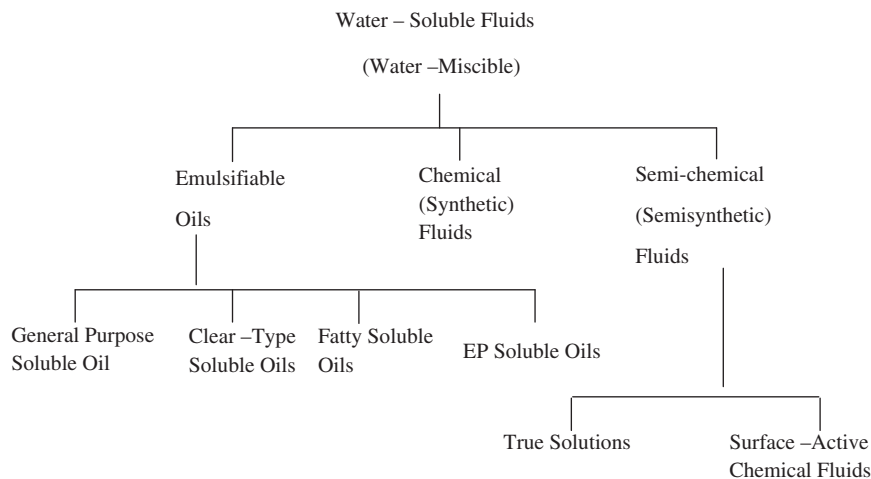


Fig. 1. Classification of water-soluble fluids [18].

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 outperformed mineral base-oils in antiwear and friction [22,25], scuffing load capacity [26] and fatigue resistance [27]. 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 [28–33]. At extreme loads, vegetable oil-based lubricants become significantly less effective [34]. 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 [35] evaluated the performance of a range of mineral and vegetable oil-based cutting fluids in a wide range of machining operations and found that vegetable-based oil formulations displayed equal or better performance than the reference commercial mineral oil in all operations. In summary, vegetable oils do display many desirable characteristics, which make them very attractive lubricants for many practical applications. Table 1 shows the advantages and disadvantages of vegetable oils as metalworking fluids.

The major performance issues such as 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 [37,38]. In this study, the application of vegetable oil-based metalworking fluids in machining various grades of steel have been reviewed in details and their applications as an alternative to mineral based oil are highlighted.

2. Application of vegetable oil-based MWFs in machining ferrous metals

The machinability of ferrous alloys 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 these materials. Hence, vegetable oil-based MWFs are 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. The machinability of various ferrous metals with vegetable oil-based MWFs as cutting fluids is discussed in the subsections that follow.

2.1. AISI 304 austenitic stainless steel

Xavior and Adithan [39] 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 rate and types of cutting fluids as critical input parameters. The levels of these parameters are presented in Table 2.

Table 2
Critical parameters and their levels [39].

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

A model calculation using multiple linear regression models were developed to determine the tool wear and surface roughness; while, ANOVA was used to determine the significant parameters that influenced the tool wear and surface roughness. The results obtained as shown in Fig. 3 indicated 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 rate 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 rate 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.

Kuram et al. [40], 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 [41]. Table 3 shows the characterization of vegetable-based cutting fluids developed for the study.

They considered spindle speed, feed rate 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 rate of 0.12 mm/rev and depth of 21 mm., while in the second set, they studied the effect of feed rates (0.08, 0.12, 0.16 mm/rev) at a

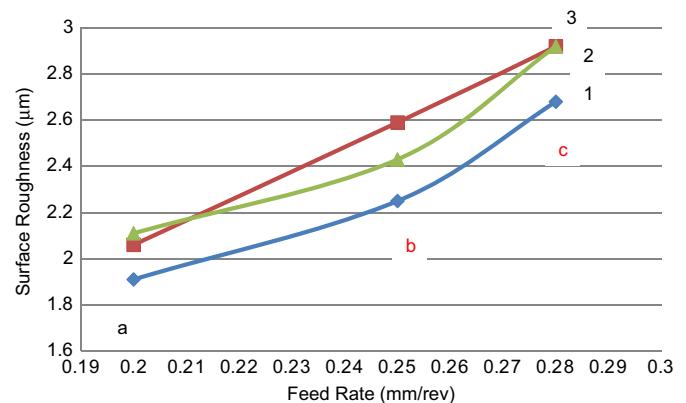


Fig. 3. Feed rate vs. surface roughness. (1) Coconut oil (2) soluble oil (3) straight cutting oil; depth of cut (d): 0.5 mm (constant); cutting speed (V_c): 38.95 m/min, 61.35 m/min and 97.38 m/min at the three points a, b and c, respectively [39].

Table 3
Characterization of vegetable-based cutting fluids [40].

MWFs ^a	pH value (emulsion 8%)	Density (g/ml)	Viscosity (40 °C) mm ² /s		Flash point (°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

^a 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.

Table 4
Characterization of vegetable-based cutting fluids [49].

MWFs ^a	pH value (emulsion 8%)	Density (g/ml)	Viscosity (40 °C) mm ² /s		Flash point (°C)	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

^a 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.

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 rate of 0.12 mm/rev and drilling depth of 21 mm, which was consistent with the literature [42–44];
- (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 rate decreased and this was consistent with previous findings [43,45,46];
- (iv) at a feed rate 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 [42,43,47,48].

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 at higher spindle speeds. 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 rate of 0.08 mm/rev. SCF-II lubricant resulted in minimum surface roughness at feed rates lower than 0.12 mm/rev.

Kuram et al. [49] performed extensive research on two different vegetable oil-based cutting fluids developed from refined canola and sunflower oil 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). Taguchi L_9 (3^4) orthogonal array was used for the experimental plan. Cutting speed, feed rate, depth of cut and types of cutting fluids were considered as input machining parameters. Mathematical models for cutting parameters and cutting fluids were obtained from regression analyses to predict tool wear and forces. S/N ratio and ANOVA were also performed to identify the significant parameters influencing tool wear and forces. Table 4

Table 5
Machining parameters and their levels [49].

Level	Cutting speed (m/min)	Feed rate (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

shows the characterization of vegetable oil-based cutting fluids used for the research.

The tool wear and force model equations developed in the study are shown in Eqs. (1)–(3).

The tool wear model:

$$VB = 0.216 - 0.00618V - 0.33f + 4.42a_p + 0.0598CF \quad (1)$$

The force model:

$$F_X = -110 + 0.113V + 210f + 877a_p - 0.2CF \quad (2)$$

$$F_Y = -75 + 0.007V + 83f + 843a_p + 1.0CF \quad (3)$$

where VB =tool wear in mm, V =cutting speed in m/min, f =feed rate 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 5.

The multiple linear regression analysis used for the modelling 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 rate (0.20, 0.25 and 0.30 mm/rev); depth of cut (0.2, 0.3 and 0.4 mm) 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 rate, 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 rate, 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 rate, 0.2 mm depth of cut and SCF-II (8%EP);
- (iv) the depth of cut was found to have a greater influence on the tool wear and force components.

2.2. AISI 1040 steel

Krishna et al. [50], 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 nonsolid lubricant suspensions in lubricating oil. The experiments were conducted under the following conditions; cutting speed (60, 80 and 100 m/min); feed rate (0.14, 0.16 and 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 inserted 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 temperatures. Fig. 4a shows that cutting temperatures increased with cutting speed irrespective of the lubricant, and cutting temperatures were less with coconut oil

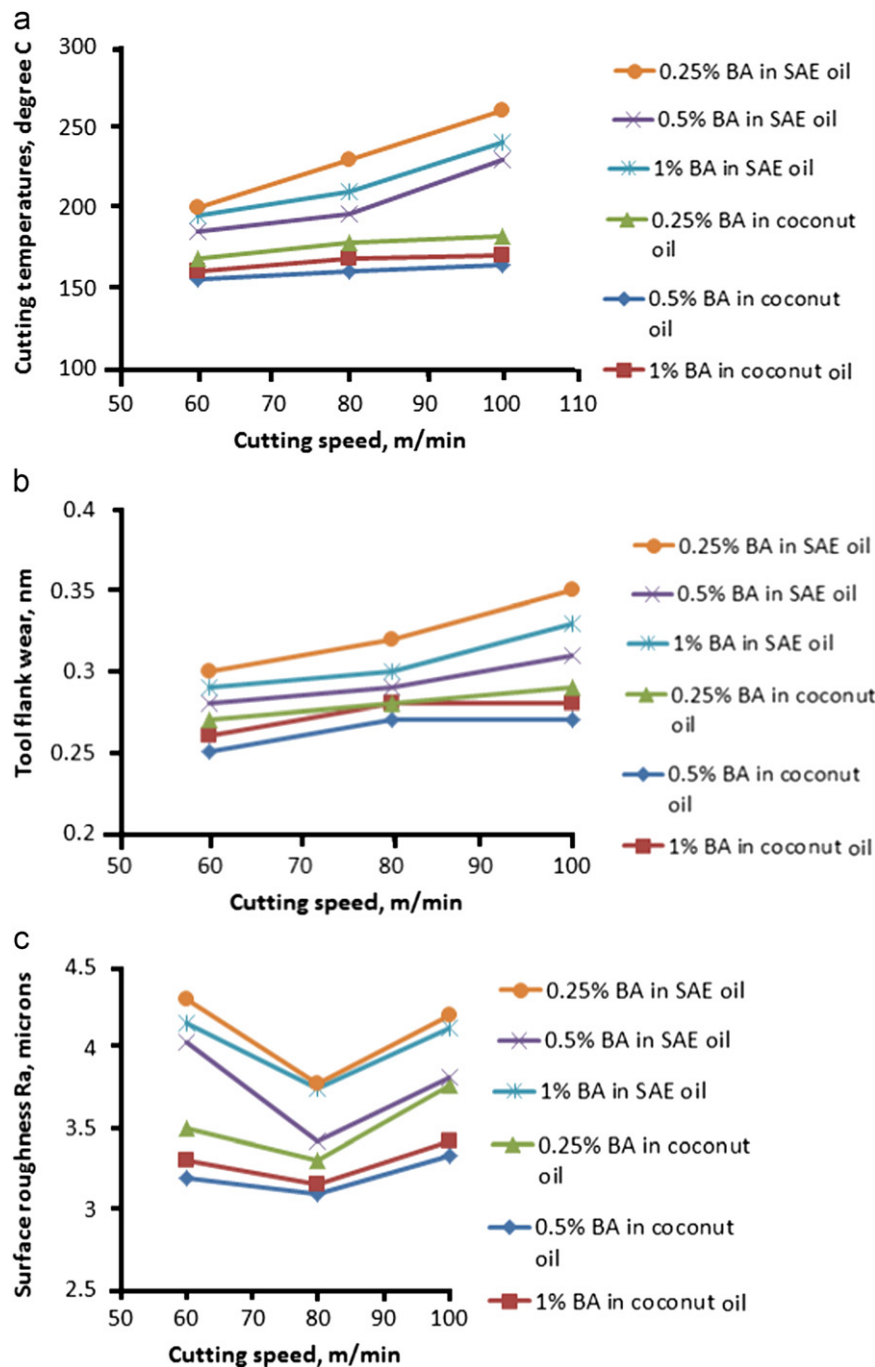


Fig. 4. (a) Variation of cutting temperatures with cutting speed (feed rate=0.2 mm/rev, d.o.c=1 mm, time=15 min) [50], (b) variation of tool flank wear with cutting speed (feed rate=0.2 mm/rev, d.o.c=1 mm, time=15 min) [50] and (c) variation of surface roughness with cutting speed (feed rate=0.2 mm/rev, d.o.c=1 mm, time=15 min) [50].

compared to SAE-40 for identical cutting conditions. Also, cutting temperatures increased with increase in feed rate 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 rate. 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 shown in Fig. 4b.

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 rate. 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 as depicted in Fig. 4c.

In addition, they concluded that, cutting temperatures, tool flank wear and surface roughness decreased significantly with nanolubricants compared to base oil due to the lubricating action of boric acid and that in all the cases, coconut oil-based nanoparticle suspensions showed better performance compared to SAE-40 based lubricant. This was because of better lubricating properties of the base oil.

2.3. AISI 420 steel

Sharif et al. [51] evaluated the feasibility of vegetable oil-based palm oil as a cutting lubricant through the use of minimum quantity lubricant (MQL) during end milling of hardened stainless steel (AISI 420) using coated carbide tool materials (TiAlN and AlTiN). Cutting forces, tool life and surface roughness were evaluated under the following machining conditions, cutting speed (100, 130 and 160 m/min), feed rate (0.05 mm/tooth), axial depth of cut (12 mm), radial depth of cut (1 mm). The end mill cutter had 10 mm with 4 flutes. The cutting fluids and lubricants used were fatty alcohol, palm olein, palm olein with additive A and palm olein with additive B.

From the cutting test shown in Fig. 5, 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 160.27 min for palm oil lubricant, followed by 137.74 min for fatty alcohol, 39.86 min for flood cutting and 35.16 min 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. However, 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, as shown in Fig. 6.

2.4. AISI 9310 alloy steel

Khan et al. [52] studied the effects of minimum quantity lubrication (MQL) by vegetable oil-based cutting fluid on turning performance of AISI 9310 low alloy steel using 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 rate (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 increase in cutting velocity and feed rate, average chip–tool interface temperature increased as depicted in Fig. 7. They found that the form (shape and colour) and thickness

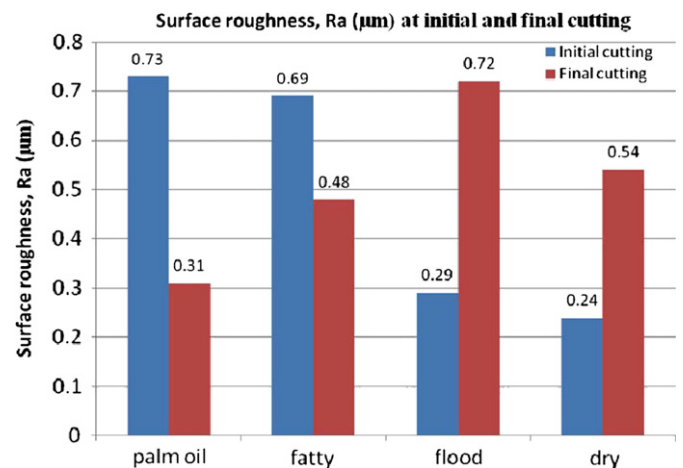


Fig. 6. Surface roughness at initial and final cutting for end milling stainless steel [51].

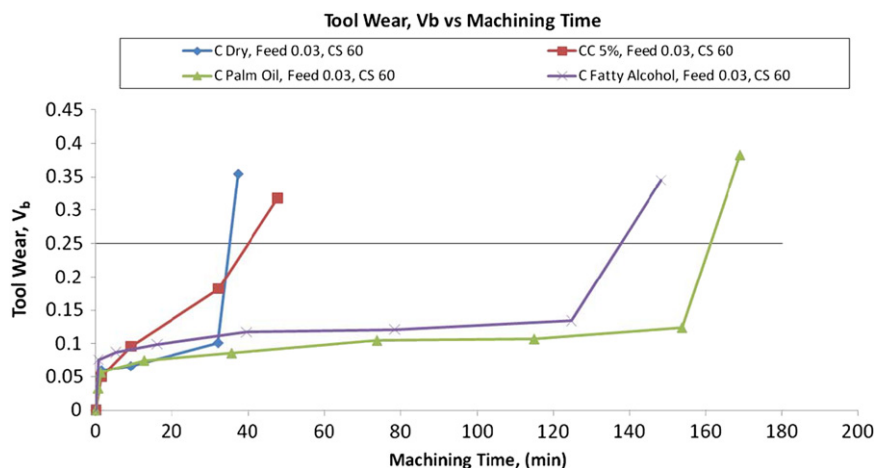


Fig. 5. Tool wear, Vb using different types of coolant conditions [51].

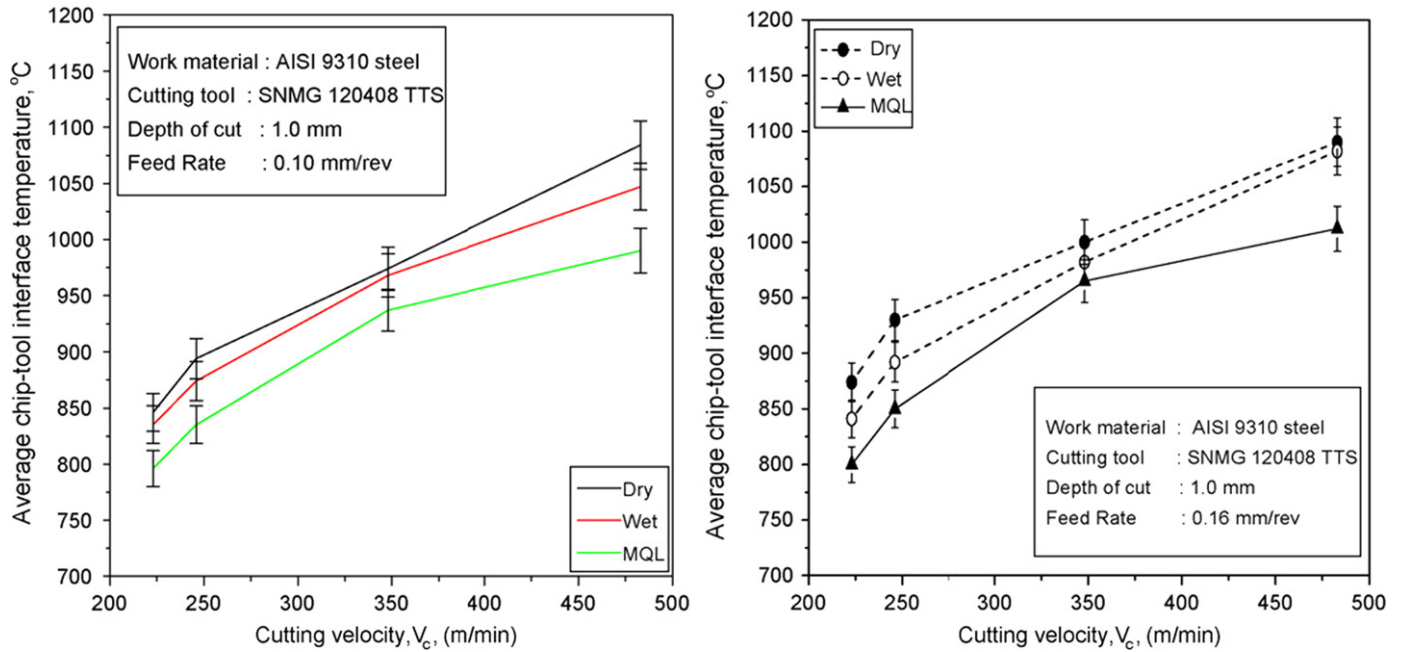


Fig. 7. Variation in average chip-tool interface temperature with cutting velocity and feed rate in turning steel by uncoated carbide tool under dry, wet and MQL cooling conditions at 0.16 and 0.18 mm/rev [52].

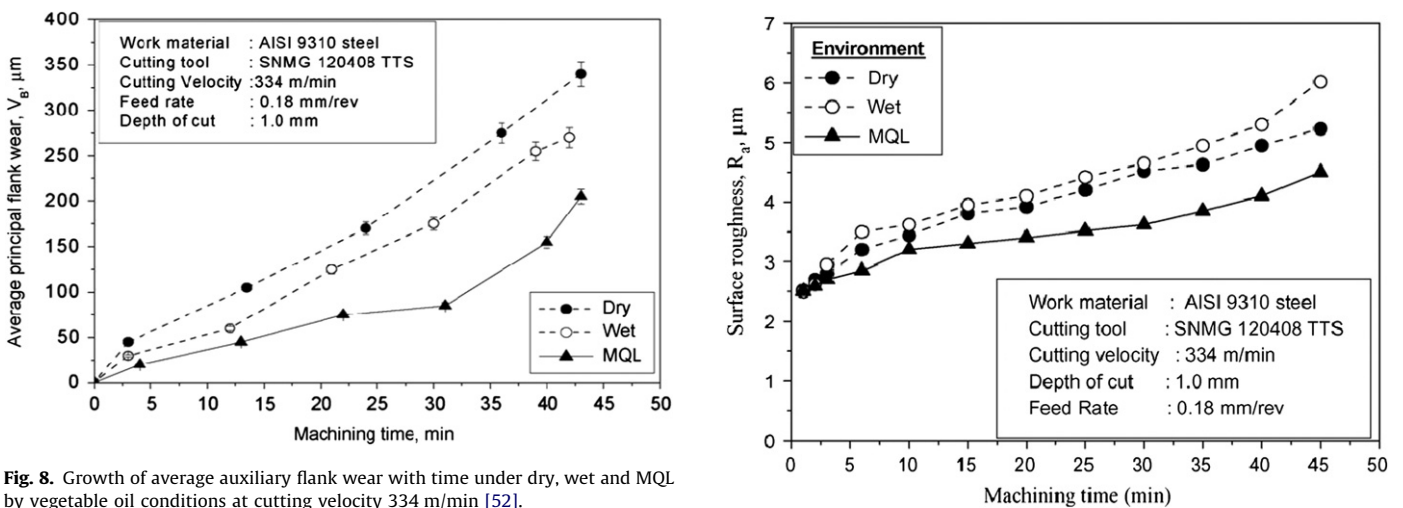


Fig. 8. Growth of average auxiliary flank wear with time under dry, wet and MQL by vegetable oil conditions at cutting velocity 334 m/min [52].

of the chips directly or indirectly indicated the nature of chip-tool interaction influenced by the machining environment. This depended on the mechanical properties of the work material, tool geometry particularly the rake angle, levels of cutting velocity and feed rate, 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 the cutting velocity and feed rate, 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 as shown clearly in Fig. 8.

The variation in surface roughness observed during turning AISI 9310 low alloy steel by uncoated carbide tool at a particular set of

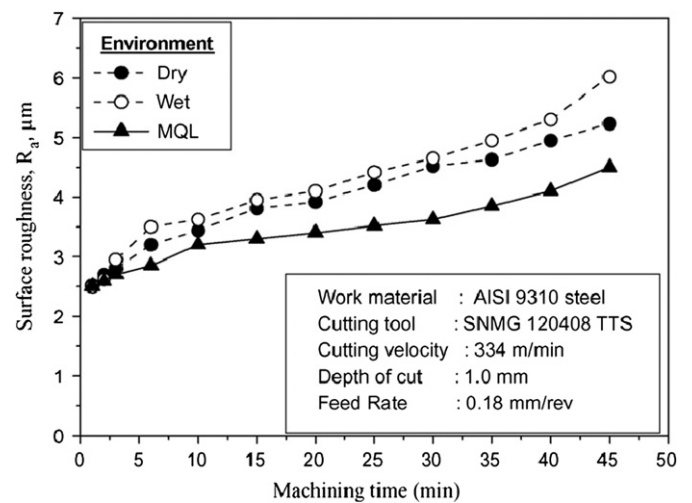


Fig. 9. Variation in surface roughness with progress of turning steel by SNMG insert under different cooling conditions at cutting velocity 334 m/min and feed rate 0.18 mm/rev [52].

cutting velocity, feed rate and depth of cut under dry, wet and MQL conditions is shown in Fig. 9. 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. It was observed from Fig. 8 that surface roughness increased quite fast under dry machining due to temperature. MQL appeared to be effective in reducing surface roughness.

One of the conclusions reported by Khan et al. [52] was a significant increase in the machining of AISI 9310 low alloy steel with carbide insert and this resulted in reduction of flank wear. Higher cutting velocity of 334 m/min and feed rate of 0.18 mm/rev were attained, which translated into improvement of metal removal rate (MRR), that is, productivity as shown in Figs. 8 and 9.

They argued that such reduction in tool wear was possible because of retardation of abrasion, decrease or prevention of adhesion and diffusion type thermal sensitivity wear at the flanks and reduction of built-up edge formation, which accelerated wear at the cutting edges by chipping and flaking. Krahenbuhl [53] reported that vegetable oils-based cutting fluids were viable alternative to petroleum-based metalworking fluids due to the following reasons: (i) vegetable oil possess higher flash point, which give opportunities for increase in MRR, because of reduction in smoke formation and fire hazard during machining process, (ii) vegetable oils provide lubricating film layer, which helps to improve workpieces quality and overall process productivity reducing friction and heat generation.

Krahenbuhl [54] reported an instance, where vegetable oil technology made it possible to increase production volume by 10%, because higher cutting velocity and feed rate were achieved and also reducing tool cost by 50% 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 had demonstrated an ability to deliver machining performance that in most applications was significantly superior to that of mineral oils and synthetic formulations.

2.5. Mild steel

Ojolo et al. [55], 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 aluminium) using tungsten carbide tool. The cutting variables considered during machining process were cutting speed, feed rate and depth of cut. Spindle speeds of 250, 330, 450 and 550 rpm were used at a constant feed of 0.15 mm/rev and 2 mm depth of cut for each of the 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 aluminium 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 the three workpieces. Lawal et al. [56] experimentally confirmed the conclusion of Ojolo et al. [55] 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 rate (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 °C was recorded by dry machining at cutting speed of 260 m/min, followed by palm kernel oil (104.36 °C), palm oil and olive oil (93.98 °C) and soluble oil (82.72 °C). The best performance was recorded by groundnut oil with 71.39 °C for the same cutting speed.

2.6. AISI 316L austenitic stainless steel

Belluco and De Chiffre [57] have studied the performance of vegetable-based oils in drilling AISI 316L austenitic stainless steel using conventional 'High Speed Steel' Cobutt (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 as shown in Table 6. The analysis of variance (ANOVA) [58] was performed to investigate the effect of different fluids on all measured parameters. Tool life was not significant at 95% confidence level for formulated fluid (D).

The thrust force was significant for both the whole life span of the tool and the measurements 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 was less than 7% and that all vegetable-based fluids performed better than the commercial mineral oil used as reference product.

2.7. Mild steel (SAE 1020)

Alves and Oliveira [59] 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 new 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 μ m, the peripheral disk dresser velocity (V_r)=38 m/s and dressing depth of cut (a_d)=10 μ m. Successive dressing strokes of 10 μ m 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 μ m 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 of chips agglomeration and this increased the friction between workpiece and wheel leading to increase in wheel wear. They reported high roughness values for the two cutting fluids with high viscosity (cutting oil and the

Table 6

Cutting fluid description: basic characteristics of tested fluids [57].

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

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

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 (ranged 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 environmental friendly.

2.8. 100Cr6 Alloy (hardened bearing steel)

Herrmann et al. [60] 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 mm³/(mm s). Technical assessment, life cycle assessment and life cycle costing were considered to evaluate the cutting fluids. The flash point and viscosity of the developed esters were observed to meet the general requirements for cutting fluids. Grinding forces obtained as shown in Fig. 10 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 have been 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 [61]. A system output of 1000 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. 11.

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 7. The authors noted the market prices in relations

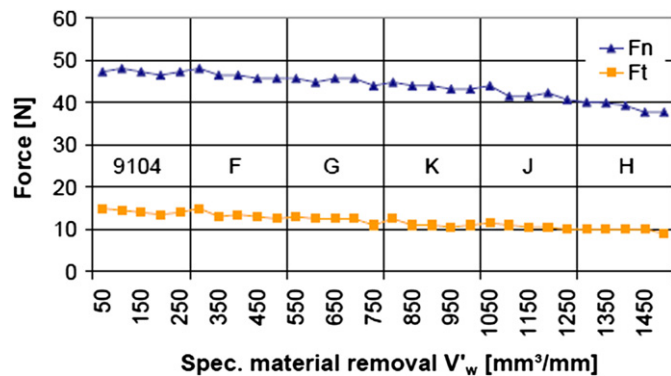


Fig. 10. Grinding forces using methyl esters as coolant [59]; 9104 (reference product—vegetable), F (animal fat methyl ester), G (used cooking oil methyl ester), K (suet methyl ester), J (lard methyl ester), H (oleic fraction methyl ester).

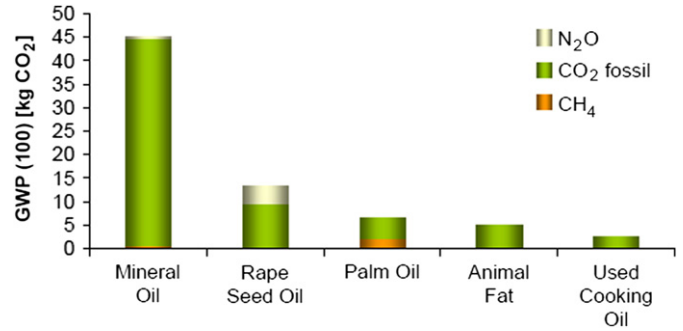


Fig. 11. Global warming potential [59].

Table 7 Market prices for different types of coolant [59].

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

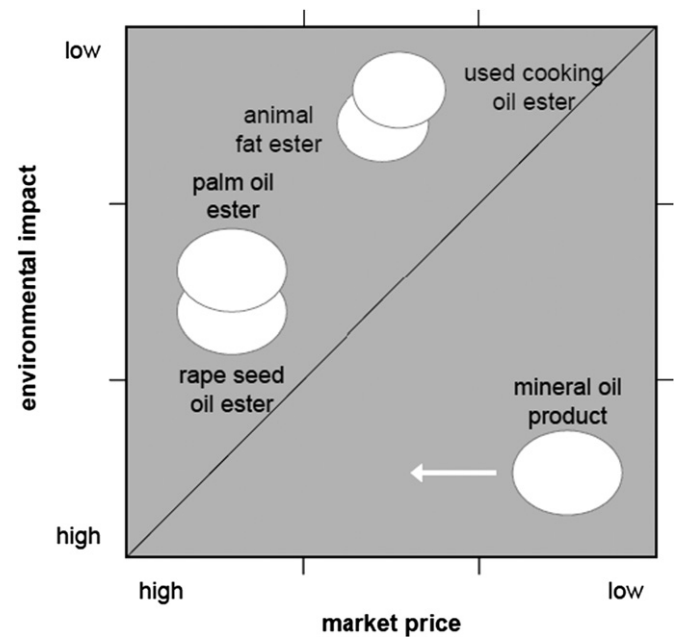


Fig. 12. Market price/environmental impact portfolio [58].

to the potential environmental impact and concluded that mineral oil product offered cheapest price while causing the biggest potential harm to the environment as shown in Fig. 12.

2.9. AISI 4340 steel

Avila and Abrao [62] 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) in dry cutting when continuous turning of hardened AISI 4340 steel (49HRC) using mixed alumina inserts (Al₂O₃+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 50–100 m/min for a feed rate (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 200–400 m/min for a feed rate of 0.05 mm/rev and depth of cut of 0.5 mm. The tests were conducted according to ISO 3685 [63] 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 rate 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 rate 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 $a_p=2.0$ mm, the lowest surface roughness values were as follows: $R_a=1.7$ μ m (dry cutting), $R_a=1.73$ μ m (fluid A), $R_a=1.89$ μ m (fluid B) and $R_a=2.14$ μ m (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 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.

3. Research and development challenges in the application of vegetable-oils based MWFs

Research and development (R & D) in the application of vegetable oil-based MWFs in machining processes have witnessed a great attention in recent years, due to the performances recorded during machining processes. The current attention to the environmental impacts of industry by governmental regulations is another factor. However, just like all other aspects of technology, R & D is an ongoing concern in the application of vegetable-oil during machining processes. A critical look at literature on the application of vegetable oil-based MWFs indicates that, it is widely used in machining of various ferrous metals. There are many of these vegetable-oils based MWFs in the market today and some of the examples of commercial MWFs based vegetable-oils are (i) Desigreen: 100, 120, 215, 300, Desiclean: 1000, Desigreen based-12, Desigreen penetrant [64], (ii) ECOLUBE [65] and (iii) CIMFREE VG: 920M, 990M, 901ZH, 3900H, 703ES, S175, S110P, MF5350 [66]. Some of these products are used for medium to heavy-duty machining and grinding processes and are applicable to ferrous and non-ferrous metals.

From the available literature, it was observed that, there had been a gap in the application of vegetable-oils based MWFs on non-ferrous and super alloy materials. Few attempts have been made in the application of MWFs during machining of non-ferrous metals like aluminium, copper and brass [55,67]. However, much work still needed to be done in the application of vegetable-oils MWFs in machining of super alloy materials. Super alloy materials which were classified into nickel base, iron base and cobalt base by Choudhury and El Baradie [68] currently occupy a very important position in manufacturing industry, as they have vast applications in engineering fields. Super alloys are known to be heat-resistant alloys of nickel, nickel–iron, or cobalt,

that exhibit a combination of mechanical strength and resistance to surface degradation that are generally unmatched by other metallic compounds. This statement calls for urgent need to focus more attention on research and development in the application of vegetable-oils based MWFs in the machining of super alloy materials. The results of investigation of the effect of palm oil as MQL lubricant on high speed drilling of titanium alloys by Rahim and Sasahara [69] shows that vegetable-oils MWFs have great potential in machining of super alloy materials.

4. Conclusion

Cooling and lubrication in machining are important in reducing the severity of the contact processes at the cutting tool-workpiece interface. Historically, more than 100 years ago, water was used mainly as a coolant due to its high thermal capacity and availability [70,71]. Corrosion of parts and machines and poor lubrication were the drawbacks of such a coolant. Mineral oils were also used at this time as these have much higher lubricity, but the lower cooling ability and high costs restricted their use for low cutting speed machining operations. It was later discovered that oil added to water (with a suitable emulsifier) gave good lubrication properties with good cooling effects and these became known as the soluble oils, but with environmental challenges to address. Currently, there are wide scale evaluations of the use of MWFs in machining, so as to reduce the amount of lubricants in metal removing operations. Kalhofer [72] revealed the main side effects of MWFs to be respiration and skin problems. An attempt to solve these problems as studied by Klocke and Eisenblatter [73] demonstrated the interest of dry machining and eventually met with success in the field of environmental friendly manufacturing. However, these became less effective when higher machining efficiency, better surface finish quality and severer cutting conditions are required. Krahenbuhl [53], therefore, suggested vegetable oils as a viable alternative to petroleum, considering the subject from performance, cost, health, safety and environmental points of view. This work is therefore a review of recent researches in the application of vegetable oil-based metalworking fluids during machining of ferrous metals. The review focuses on the performance and environmental impact of these vegetable oils as emulsion and straight oils for various materials and machining conditions. The salient features are as follows:

1. The introduction of vegetable oil-based metalworking fluids in machining applications has made it possible to achieve better performance as reported by all researchers. Coconut oil showed the best performance at cutting speed (90 m/min), depth of cut (1 mm) and feed rate (0.35 mm/rev) when compared to mineral oil on turning of AISI 304 austenitic stainless steel. Surface roughness (R_a) of 4.5 μ m and 5.5 μ m were obtained respectively for coconut oil and mineral oil.
2. Palm oil-based cutting fluids used in milling of AISI 420 stainless steel was observed to yield longer tool life of 160.27 min and surface roughness of 0.31 μ m compared to fatty, flood and dry cutting with 137.74, 39.86 35.16 min tool lives and 0.48, 0.29, 0.24 μ m surface roughness, respectively.
3. When vegetable oil was applied to turning of AISI 9310 alloy steel using MQL mode of application, there was remarkable improvement of metal removal rate (MRR), that is, productivity. High productivity means that higher feed rate was achieved when vegetable-oil-based metalworking fluid was used. Surface roughness values of 4.0, 5.0 and 5.5 μ m were obtained for vegetable-oil, wet and dry cutting, respectively, at cutting velocity of 334 m/min and feed rate of 0.18 mm/rev.

4. Vegetable oil-based metalworking fluid is being recognized as having superior lubricating properties compared to other based-oil. The use of these coolants has improved significantly the machining performances with reported increase of 117% in tool life and 7% reduction in thrust force. An increased machining performance and lower environmental impact can be obtained with vegetable oils-based cutting fluids. However, vegetable oil-based metalworking fluids are good as metalworking fluids during machining process and their relative effects in improving product quality and reducing cutting force is work material dependent.
5. Sunflower oil-based cutting fluid used during the drilling of AISI 304 austenitic stainless steel material and high speed steel E-grade tool had the least thrust force at spindle speed of 720 rpm. The least surface roughness was reported at spindle speed of 720 rpm when commercial vegetable cutting fluid was used. When the spindle speed was increased from 520 to 720 rpm, the surface roughness decreased by up to 32% for sunflower cutting fluid. Sunflower cutting fluids (a mixture of two surfactants and commercial vegetable cutting fluid) had low surface roughness at feed rate of 0.12 mm/rev. Sunflower cutting fluid had the least surface roughness of 2.04 μm at feed rate of 0.12 mm/rev.
6. The combined effect of solid lubricant and vegetable-oil when used in turning of AISI 1040 steel with cemented carbide tool led to the reduction in flank wear. Surface roughness of 3.2 μm was reported for coconut oil with 0.5% nanoboric acid particles suspensions, while surface roughness of 3.5 μm was obtained for SAE-40 oil. Cutting temperatures of 160 °C and 200 °C were obtained for coconut oil and SAE-40 oil, respectively. The flank wear values of 0.26 and 0.28 mm were reported for coconut oil and SAE-40 oil, respectively.
7. In turning of AISI 4340 steel with alumina insert, three types of cutting fluid produced three different surface roughness values. When using emulsion without mineral oil, surface roughness was 1.73 μm , while for synthetic emulsion, the roughness was 1.89 μm and that of emulsion with mineral oil was 2.14 μm . It was observed that the application of cutting fluid based on emulsion without mineral oil resulted in longer tool life compared to dry cutting.

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