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Vegetable-oil based metalworking fluids research developments for machining processes: survey, applications and challenges

Sunday Albert Lawal[1,*], Imtiaz Albert Choudhury[2], Ibrahim Ogu Sadiq[1], and Adedipe Oyewole[1]

[1] Department of Mechanical Engineering, School of Engineering and Engineering Technology, Federal University of Technology, Minna, Nigeria
[2] Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, Malaysia

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Abstract – Research developments in the application of vegetable-oil based metalworking fluids (MWFs) in machining processes have witnessed a great attention in recent years, this being due to the environmental friendliness and performances recorded while machining. In the work reported in this paper, the authors surveyed relevant literatures, identified gaps in the application of vegetable-oil based MWFs, and proposed challenges and needs to fill the gaps created as a result of new development in engineering material applications. The engineering materials for the machining processes addressed were classified into three categories: ferrous materials, non-ferrous materials and super alloys materials. This survey is both timeline and process defined. It identified gaps in the research developments at various periods of time with respect to applications to various processes. It concluded by making a case for application of vegetable-oil based MWFs for milling and grinding processes and super alloy materials as a way of addressing environmental impact that is always associated with application of mineral-oil based MWFs.

Key words: Metalworking fluids, Machining, Vegetable oil, Materials for machining

1. Introduction

Metalworking fluids (MWFs) are engineering materials that optimize metalworking processes such as turning, grinding, drilling and milling. In manufacturing and engineering communities, they are used for metal removal purpose and are known as cutting and grinding fluids, while fluids used for drawing, rolling and stamping processes are known as metalforming fluids. Metalworking fluid is one of the many types of lubricants, which are extensively used in machining processes and there are several types, which may be used to carry out such tasks [1]. The mechanics of metalworking which governs the requirements for metalworking fluids includes (i) the ability of the fluid to provide a layer of lubricant to act as a cushion between the workpiece and the tool, in order to reduce friction, (ii) functions as a coolant to reduce the heat produced during machining or forming, (iii) prevent metal pick up on both the tool and workpiece by flushing away the chips as they are produced, (iv) produce the desired finish on an accurate piece-part. The impetus in the days of the industrial revolution, is to machine or form part at the highest rate of speed with maximum tool life, minimum downtime and the fewest possible part rejects (scrap), all while maintaining accuracy and finish requirements, which can only be achieved by metalworking fluids properties [2].

A review of the literature on vegetable-oil based metalworking fluids in this survey is both era and application defined. Due to the volume of work and amount of literature available on MWFs research, it was necessary to define a realistic scope for this study. Hence, the study assessed the past and current application of vegetable-oil based MWFs in machining processes application; current developments in engineering materials for manufacturing purposes and identified gaps in vegetable-oil based MWFs applications along machining processes classification and charted a course for future research directions.

2. Literature survey

2.1. Early research era (early metal age – 1900 AD)

A review of the trend of current research would be baseless, if attempt is not made to consider the research findings of the previous era, so as to know what research gaps need attention. It is often said that, "*a river that forget its source, will suddenly or eventually run dry*". Therefore, the main purpose of including this early era in this review is to establish a baseline research direction and gaps, in order to assess how

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*e-mail: `lawalbert2003@yahoo.com`

well current research has addressed the need for vegetable-oil based metalworking fluids in machining processes. 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 [3]. The early metal age (ca 2000 BC–AD 300) also refers to as the bronze age and early iron age in Fennoscandia was characterized by more intensive networks of hunter – gatherers, which can be seen in the use of various wide – spread tools [4], while the late metal age (AD 300–700) in the north of Fennoscandia was characterized by few findings in iron weapons and iron spearheads and axes obtained by exchange trade from abroad [5]. Though, no mention of application of metalworking fluids at this stage, but at later years, 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 [6]. Schey [3], pointed out in his book "Metal Deformation Processes" that metalworking is probably humankinds first technical endeavour and considering the importance of lubricant used in the process, he was, amazed to note that no record of their use were recorded until after some time. In 1735, Leupold recommended that tallow or vegetable oil should be used for lubricating rough surface [6]. In the 19th century, the means to mitigate frictions and wear through lubrication were investigated leading to the Reynolds' theory of fluid film lubrication and in early 20th century, Hardy with Doubleday introduced the concept of boundary lubrication [3]. However, it was not the development of scientist theory that ultimately led to the explosion of research in this area and especially on the mechanics of metalworking and metalforming fluids in the 20th century. Rather, it was the wealth of mechanical inventions and evolving technologies that created the need for understanding the nature of friction and wear and how these effects can be mitigated by proper lubrication. The lack of early information on machining fluids can only be attributed to reluctance on the part of the craftsman, seen even today on the part of manufacturers, to disclose certain aspects regarding the compounding of the fluids. It has been observed that the machine tool industry could not have progressed to where it is today, without the significance of the technological development of metalworking fluids. The development of metalworking fluids was the catalyst permitting the development of energy – efficient machine tools having the high speed and feed capacities required for today's production needs for extremely fast forming and metal cutting operations [2]. Water was used as the cutting fluid in grinding machines around 1575 by Jonnes Stradanus. An indication that oil was also used as a metalworking fluid was illustrated in Leonardo's design for an internal grinding machine. In 1838, James Whitelaw developed a cylindrical grinding machine for grinding the surface of pulleys wherein "a cover" was provided to keep in the splash of water [7].

James H. Nasmyth in his 1830 autobiography described the need for a small tank to supply water or soap and water to the cutter to keep it cool. This simple arrangement was used to hold the coolant to drip directly on the cutter, while machining [8]. About 50 years after the industrial revolution (1850–1900), there was growing awareness of the value of metalworking fluid as a solution to many of the machining problems emerging from the new demands upon the machine tools. The following four significant events made conditions ripe for rapid progress in the development of compounded metalworking fluids (i) the discovery of huge quantities of petroleum in the US in 1859 led to profound influence on the compound of metalworking fluids, (ii) the development of alloy steels for making tools, (iii) budding petrochemical industry, (iv) development of electric motor as a power source [2]. Northcott [9] reported that Lathe productivity could be materially increased by using cutting fluids and the exhibition of machine tool of 1873 held in Vienna reported the widespread use of metal removal operations in both England and the United States of America. In 1870, Thurston found out that sperm oil was superior to lard oil when cutting steel and the experiment on cutting metal conducted by Fredrick W. Taylor in 1883 proved that directing a constant heavy stream of water at the point of chip removal increased the cutting speed that the output of the experimental machine rose by 30–40% [10].

2.2. Current research developments (1900-till date)

This period will be discussed with special focus on application of vegetable-oil based metalworking fluids on different machining processes (turning, drilling, grinding and milling). From available literature, it was observed that, there has been a gap in the application of vegetable-oil based MWFs in machining processes and materials types (ferrous, non-ferrous and super alloy materials). However, the status of vegetable-oil based metalworking fluids between 1900 and 1950 witnessed another challenge, as metalworking fluids industry provided machinist with a choice of several metalworking fluids, such as straight mineral oils, combinations of mineral oils and vegetable oils, animal fats (lard and tallow) marine oils (sperm, whale and fish) mixes of free sulphur and mineral oil used as cutting oils and "sud" [2]. As alloy steels were developed, machine tool, cutting tool speeds increased, the stresses incurred in the machining process tended to overwork the cutting oils. 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. In 1924, special sulfo-chlorinated oil was patent by one of the oldest lubricant compounding companies in the United States and marketed as Thread-Kut 99 and still being used today for heavy duty machining operations as thread cutting and broaching on steels [11]. This new highly sulfo-chlorinated cutting oils could not be used for machining brass or copper since sulphur additives stained those metals black and contributed to eventual corrosion [12]. In 1905, when chemists began to look at colloidal systems, the scientific basics of metalworking fluid formulation began to unfold. English Chemist, H.W. Huton later discovered a way to emulsify oil in water in 1915. However, the composition and components of this product were not described [13]. He was granted a patent for the process of producing water soluble oils by compounding sulfonated and washed castor oil with any sulfonated unsaponified fatty oil (other than castor oil) and then saponifying the sulfonated oils with caustic alkali [14]. The knowledge on colloid and surfactant chemistry led to the compounding of various "soluble oils" using natural fatty oils.

The growth of the aircraft industry, exotic alloys of steel and non-ferrous materials during the World War II created the need for more powerful machine tools having greater capacity and as a result of this demand, metalworking fluids along with machine tools were at the heart of the cutting process [2]. Ernst studied the physics of metal cutting and determined that a rough and torn surface is caused by chip particles adhering to the tool causing a built-up edge (BUE) on the nose of the cutting tool due to high chip friction. He discovered the application of a cutting fluid lowered the chip friction and reduced or eliminated the BUE [15]. Merchant, in another study, was able to measure temperatures at the chip-tool interface. He discovered that in this area, heat evolves from two sources, the energy used up in deforming the metal and the energy used up in overcoming friction between the chip and tool and argued that almost two thirds of the power required to derive the cutting tool is consumed by deforming the metal and the remaining third is consumed in overcoming chip friction. Merchant found that the right type of cutting fluid would greatly reduce the frictional resistance in both metal deformation and chip formation, as well as reduce the heat produced in overcoming friction [16]. Bisshopp et al. [17] also investigated the role of the cutting in machining experiments to determine whether or not a continuous film existed in the chip tool interface. He concluded that a continuous film as required for hydrodynamic lubricant could not exist in the case where a continuous chip was formed, neither was it possible for fluid to reach the areas where there was a chip tool contact in the irregularity of the surfaces. Schmidt et al. [18] also investigated radial rake angles in face milling and the coefficient of friction with drilling torque and thrust for different cutting speeds. Schmidt and Sirotkin [19] investigated the effects of cutting fluids when milling at high cutting speeds, he observed that depending upon which of the various cutting fluids were used, tool life increased approximately 35–150%. Ernst and Merchant [20] studied further into relationship of friction, chip formation and high quantity machined surface and their conclusion agreed with Bisshopp et al. [17] as they found that cutting fluid present in the capillary spaces between the tool and workpiece was able to lower friction by chemical action.

Shaw continued this study of the chemical and physical reactions occurring in the cutting fluid and found that even the fluid's vapours have constituents that are highly reactive with the newly formed chip surfaces. The high temperatures and pressures at the contact point of the tool and chip effect a chemical reaction between the fluid and the tool-chip interface, resulting in the deposition of a solid film on the two surfaces which becomes the friction reducing agent [21, 22]. Using machine tool cutting tests on iron, copper and aluminum with pure cutting fluids, Merchant demonstrated that this reaction product, which "plated out" as a chemical film of low shear strength, was indeed the friction reducer at the tool-chip interface. He stated that materials such as free fatty acids react with metals to form metallic soaps, and that the sulfurized and sulfo-chlorinated additives in turn form the corresponding sulfides and chlorides acting as the agents that reduce friction. However, he quickly cautioned that as cutting speeds increase, temperature increases rapidly and good cooling ability from the fluid is essential. He pointed out that at speeds of over 50 feet per minute (254 mm/s), the superior cutting fluid must have the dual ability to provide cooling as well as friction reduction capacity [23]. Having learned which chemical additives are effective as friction reducers, Ernst, Merchant, and Shaw theorized that if they could combine these chemicals with water in the form of a stable chemical emulsion, a new cutting fluid having both friction reducing and cooling attributes could be created and in 1945, as a result of this research, their company compounded a new type of "synthetic" cutting fluid [19]. The new product, described as a water-soluble cutting emulsion with the name of CIMCOOL, appeared as a news item in a technical journal in October 1945 [24].

3. Application of vegetable-oil based MWFs in machining processes

3.1. Turning process

Lawal et al. [25] evaluated the effect of vegetable and mineral oil-in-water emulsion cutting fluids in turning AISI 4340 steel with coated carbide tools. The turning process was performed on a Colchester VS Master 3250 (165 mm × 1270 mm) gap bed centre lathe rated with 7.5 kW and spindle speed of 3250 rpm. A round bar of AISI 4340 steel alloy with 90 mm diameter and 360 mm length was chosen so as to maintain a ratio of cylindrical turning length to the initial diameter of workpiece at four in order to ensure the required stiffness of chuck/workpiece/cutting force. Design of experiment using full factorial method was employed in the process of cutting fluid formulation, while the effect of formulated cutting fluids on surface roughness and cutting force in turning AISI 4340 steel with coated carbide using Taguchi method were investigated and compared with conventional (mineral) oil-in-water emulsion cutting fluid. Four factors and three levels experimental design (L_{27}) was adopted in the Taguchi method. While the machining conditions used for the experiment are shown in Table 1.

Minitab-14 statistical analysis software which is widely used in engineering application was used in the analysis of S/N (dB) ratio and ANOVA. ANOVA results show that cutting speed (64.64%) and feed rate (32.19%) have significant influence on the surface roughness and depth of cut (33.1%) and type of cutting fluids (51.1%) have significant influence on the cutting force. Similarly, Xavior and Adithan [26] 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 for 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. A model calculation using multiple linear regression models were developed to determine the tool wear and surface roughness. The results indicated that

Table 1. Process parameters and their levels [25].

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

coconut oil had greater influenced on the surface roughness and tool wear than other cutting fluids.

Khan et al. [27] studied the effects of minimum quality lubrication (MQL) using vegetable-oil based cutting fluid on turning performance of low alloy steel AISI 9310 as compared to completely dry and wet machining in terms of chip-tool interface temperature, chip formation mode, tool wear and surface roughness using uncoated carbide tool. The process parameters 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 study show that, with increase in cutting velocity and feed rate, average chip-tool interface temperature increased, even under MQL condition, due to increase in energy input and the roles of variation of process parameters. There was gradual growth of average principal flank wear observed under all the environments. 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. In another experiment conducted by Ojolo et al. [28] to determine 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. They employed the following cutting variables during turning process; cutting speed, feed rate and depth of cut. The spindle speeds of 250, 330, 450 and 550 rpm were investigated at a constant feed of 0.15 mm/rev and 2 mm depth of cut for each of the workpiece. Results show that bio oils were suitable for metal working fluids but the effects of the bio-oils on cutting force were material dependent. Lawal et al. [29] experimental result was in agreement with Ojolo et al. [28] 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.

Ojolo and Ohunakin [30] investigated the effect of cutting speed, feed rate, depth of cut, and rake angle on main cutting force during the cylindrical turning of mild steel, brass and aluminum rod, using high speed steel cutting tool and palm-kernel oil as cutting fluid. The impact of lubrication on the coefficient of friction between the chip and rake face during turning operation, assuming a negligible friction between the flank and cut surface was measured. Experimental results show reduction in coefficient of friction for all the materials under different cutting conditions using palm kernel oil as cutting fluid. In a similar development, Krishna et al. [31] 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 with nanosolid lubricant suspensions in lubricating oil. The experiment were conducted under the following conditions; cutting velocity (60, 80 and 100 m/min); feed rate (0.14, 0.16, 0.2 mm/rev); depth of cut (1.0 mm), environment (solid lubricant of boric acid); lubricating oil (SAE-40 and coconut oil); solid lubricant particle size (50 nm) and flow rate of lubricant oil (10 mL/min). The temperature was sensed by the embedded thermocouple which was placed at the bottom of the tool insert in the tool holder. They showed that the cooling action of the lubricant with nanosolid lubricant suspensions was evident from the measurement of the cutting tool temperatures as shown in Figure 1.

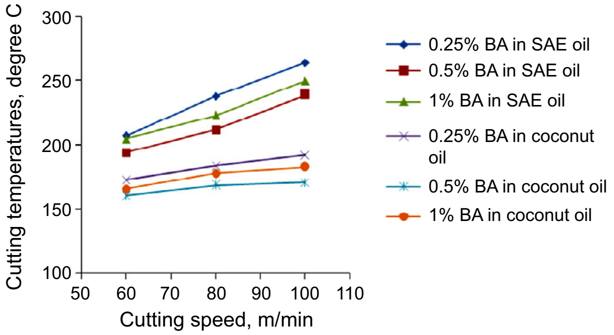

Figure 1. Variation of cutting temperatures with cutting speed (feed rate = 0.2 mm/rev, d.o.c = 1 mm, time = 15 min), Source: Krishna et al. [31].

The combined effect of solid lubricant and vegetable oil led to reduction in flank wear with 0.5% nanoboric acid particles suspensions in coconut oil compared to 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 rate. In addition, cutting temperatures, tool flank wear and surface roughness were 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, due to the better lubricating properties of the base oil.

3.2. Drilling process

Belluco and De Chiffre [32] studied the performance of vegetable-based oils in drilling AISI 316L austenitic stainless steel using conventional HSS-Co tools. The efficiencies of

Table 2. Characterization of vegetable based cutting fluids [34].

MWFs*	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

*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.

six cutting oils were evaluated by measuring tool life, cutting forces and chip formation using commercial mineral-based oil as reference product, and five vegetable-based (rapeseed oil) cutting fluids at different levels of additivation for the experiment. The analysis of variance (ANOVA) was performed to investigate the effect of different fluids on all measured parameters [33]. It was observed that 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 from the experimental result that there were relative increases 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. Equally, Kuram et al. [34] investigated 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 HSSE 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 [35]. Table 2 shows the characterization of vegetable based cutting fluids developed for the study.

The study considered spindle speed, feed rate and drilling depth as input parameters with two sets of experimental design. The first experiment 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 the second experiment studied the effect of feed rates (0.08, 0.12, 0.16 mm/rev) at a constant spindle speed of 620 rpm and drilling depth of 21 mm. The studied made the following observations (i) an increased in the spindle speed and 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 literature [36–38]. (ii) The lower thrust force values were obtained with SCF-I and the least thrust force was achieved at spindle speed of 720 rpm. (iii) The effect of feed rate and cutting fluid type on thrust force using spindle speed of 620 rev and drilling depth of 21 mm showed that, at a low feed rate, the thrust force of the hole was decreased and an increased in the feed rate increased the thrust force, which was consistent with literature [37, 39, 40]. (iv) The effect of spindle speed and cutting fluid type on surface roughness using a feed rate of 0.12 mm/rev and drilling depth of 21 mm was discovered to show that an increased in the spindle speed decreased the surface roughness value which is consistent with literature [36, 37, 41, 42]. However, the least surface roughness was achieved at spindle speed of 720 rpm using CVCF, but SCF-I was 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 was decreased by up to 32% for SCF-I. Again, it was observed that, an increase in the feed rate, increased the surface roughness for feed rate and cutting fluid type on surface roughness using a spindle speed of 620 rev and drilling depth of 21 mm, which was consistent with literature [36, 37, 41, 42]. SCF-II and CVCF had low initial surface roughness at feed rate of 0.08 mm/rev. SCF-II had the smallest surface roughness at feed rates lower than 0.12 mm/rev, which made SCF-II superior at the lower feed rates as the least surface roughness was achieved at feed rate of 0.08 mm/rev.

Kuram et al. [43] performed extensive research on two different vegetable based cutting fluids developed from refined canola and sunflower oil and a commercial type semi-synthetic cutting fluid to determine 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 experimented plan. Cutting speed, feed rate, depth of cut and types of cutting fluids were considered as machining parameters. Mathematical models for cutting parameters and cutting fluids were obtained from regression analyses to predict values of tool wear and forces. Signal-to-noise (S/N) ratio and ANOVA analyses were also performed to obtain significant parameters influencing tool wear and forces. The multiple linear regression analysis used for the modelling agreed with the results obtained for tool wear which were between the range of 0.010 and 0.980 mm for cutting speed (150, 175 and 200 mm); 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 depth of cut was found to have a greater influence on the tool wear and force components.

Rahim and Sasahara [44] studied the potency of MQL palm oil (MQLPO) and MQL synthetic ester (MQLSE) during drilling of titanium alloys with carbide drill coated with AlTiN insert. The holes were drilled under the action of the external air blow, 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 together with two feed rates of 0.1 and 0.2 mm/rev; the thrust force, torque and workpiece temperature were measured and compared. The second stage involved drilled of hole of a depth of 10 mm at the constant cutting speed of 60 m/min and feed rate of 0.1 mm/rev with the following tool life criteria (i) average flank wear, *Vb*(ave) = 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 result obtained show the flank wear rapidly grew and suffered from excessive chipping and a significant reduction of tool life and a drilling time of 48 s or 110 mm in length were obtained that air blow conditions for the air blow condition. The flank and corner wear rate was gradual and grew progressively for MQLSE and MQLPO as a tool life of 314 s (stopped at 710 mm) was recorded. It was observed that MQLPO produced lower tool wear rate in comparison to MQLSE condition. The flood condition also showed superior performance by the lowest flank wear and corner rate in comparison to air blow conditions. It was found that the air blow condition produced the highest thrust force (3388 N) in comparison to the other coolant-lubricant conditions and the highest thrust force of 3170 N was obtained by the MQLSE condition. MQLPO and flood conditions exhibited comparable and lowest thrust force among other conditions tested, as the thrust force was reduced by 30% and 6.5% relative to air blow cutting for the MQLPO and MQLSE conditions respectively.

3.3. Grinding process

Alves and Oliveira [45] studied the development of new cutting fluid for grinding process adjusting mechanical performance and environmental impact using CBN tool on SAE 1020 material. Two types of fluids were tested (cutting oil and a semi-synthetic fluid) along with new cutting fluids so as to compare the performance. The parameters evaluated were radial wheel wear, workpiece roughness and chemical analysis to show that the new fluid was not toxic and easy biodegradability. 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 and while a successive dressing strokes of 10 µm in diameter were performed until uniform profile was obtained. The study showed that the use of cutting oil caused the lower wheel wear (high grinding) and the higher wheel wear of approximately 8 µm in radius was observed when semi-synthetic cutting fluid (higher cooling ability and lower lubricant properties). However, various concentration of the formulated fluids show different results. The study equally investigated the biodegradability of the cutting fluid using "Ready Biodegradability" test. The CO_2 evolution that was absorbed by $Ba(OH)_2$ solution during the test period was determined by titration with HCl and the result obtained suggested that the cutting fluid was environmental friendly. Herrmann et al. [46] equally investigated the technical, ecological and cost assessment from a life cycle perspective of coolants made of native ester.

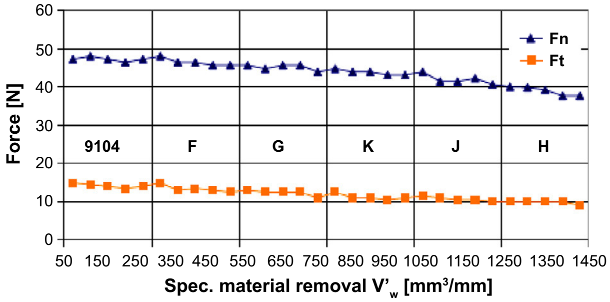

Figure 2. Grinding forces using methyl esters as coolant [59]; 9104 (reference product – vegetable), F (animal fat methyl ester), G (used cooking oil methyl ester), K (suet methyl ester), J (lard methyl ester), H (oleic fraction methyl ester) [46].

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 (Vc) = 60 m/s, wheel diameter (ds) = 40 mm, width of cut (a_p) = 10 mm, workpiece diameter (dw) = 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 cutting fluids. The flash point and viscosity of the developed esters were observed to meet the general requirements of cutting fluids. Grinding forces obtained as shown in Figure 2 indicated that a stable grinding process was possible with all tested ester oils, while the grinding force ratios stayed on the same level. It was observed that the tendency to lower force as longer the test lasted was caused by sharpening grinding wheel topography but not by the change from 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) ISO 14040 family methodology (DIN ISO, 1998) according to system output of 1000 workpieces processed with the respective lubricant to determine the environmental burdens.

3.4. Milling process

Sharif et al. [47] 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 (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), end mill diameter (10 mm with 4 flutes) and cutting fluids/lubricants (fatty alcohol, palm olein, palm olein with additive A and palm olein with additive B. It was observed

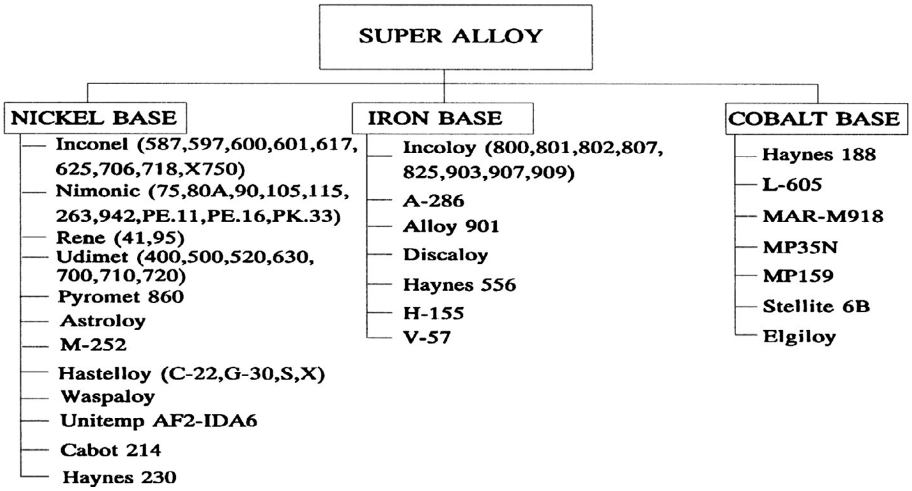

Figure 3. Classification of super alloys [49].

that, tool wear progressed gradually 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. It was noticed that the flank wear developed in three stages; primary wear phase, normal wear phase and sharp wear phase and the wear progressed rapidly with machining time for dry and flood cutting, but the tool wear increased at a low rate under the palm oil and fatty alcohol coolant. The value of surface roughness for palm oil and fatty alcohol at the initial stage were quite high. The respective values of surface roughness were 0.73 μm and 0.69 μm. But in the final stage, the value of surface roughness was lower than the value at the initial stage.

4. Limitation of vegetable-oil based MWFs

There are typical examples where metalworking fluids application whether it is vegetable or mineral based harm the process and therefore, it must not be used. Example is when machining with ceramic tools, it must be performed without fluid, because it may promote thermal shocks and eventually, cause tool breakage. Some ceramic tools, mainly those based on Si_3N_4 and the "whiskers" which have higher toughness and thermal shock resistance can avoid this kind of failure and so cutting fluid can be applied. When machining magnesium, more serious problems may occur when water based fluids are applied because water reacts with the chips, releasing hydrogen, which may cause ignition and fire hazards [48]. 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.

5. Challenges for future research development

Future research development and a case for vegetable-oil based MWFs for machining processes has been and will continue to be important to the manufacturing industries such as micro manufacturing, robotic and the military, because of the machining performance, environmental friendliness and the development of new engineering materials. This statement underscores the important and need to focus attention on machining of super alloy materials, which currently occupied a very important position in manufacturing industry as they have vast application in engineering fields. This is because the available literature shows that not much has been done in the investigation of effect of vegetable-oil based metalworking fluids on super alloy materials. Super alloy materials 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 generally unmatched by other metallic compounds. The primary uses of these alloys includes (i) aircraft gas turbines, e.g. disks, combustion chambers, bolts, castings, shaft exhaust systems, blades, vanes, etc.; (ii) steam turbine power plants e.g. bolts, blades, stack gas re-heaters; (iii) reciprocating engines e.g. turbocharger, exhaust valves, hot plugs, etc.; (iv) metal processing e.g. hot work tool and dies, casting dies; (v) medical applications e.g. dentistry uses, prosthetic devices; (vi) space vehicles; (vii) heat-treating equipment; (viii) nuclear power systems; (ix) chemical and petrochemical industries; (x) pollution control equipment and (xi) coal gasification and liquefaction systems. These super alloys (Ni, Fe-Ni, Co based) are further sub-divided into wrought, cast and powder metallurgy alloys [49]. Figure 3 shows the classification of the super alloys.

There is an urgent need and a recommendation that research development should move in the directions of these materials, if the advantages of vegetable-oil based MWFs over mineral oil-based MWFs are to be harnessed and sustained. The trend in machining is moving towards dry or near dry cutting in order to reduce the consumption of cutting fluids as stressed by Weinert et al. [50]. But even with the most advanced tool materials and coatings, it seems that lubricants in the case of hard-to-cut materials (super alloys) such as nickel-based alloys cannot be completely avoided [51]. The first research work reported on non-mineral oil based metalworking fluids was by Thurston in 1870, when he discovered

Table 3. Summary of research in the application of vegetable oils-based MWFs for machining processes.

Machining process	Workpiece material	Tool material	Type of cutting fluid	Investigation	Author(s)
Turning	AISI 4340 steel	Coated carbide	Palm kernel and cottonseed oil-in-water emulsions and mineral oil emulsion	Cutting force and surface roughness	Lawal et al. [25]
Turning	AISI 304 steel	Carbide	Coconut oil, emulsion and neat cutting oil immiscible with water	Tool wear and surface roughness	Xavior and Adithan [26]
Turning	AISI 9310 steel	Uncoated carbide	Vegetable oil (type not specified)	Temperature, chip formation, tool wear and surface roughness	Khan et al. [27]
Turning	Mild steel, aluminum and copper	Tungsten carbide	Groundnut, coconut, palm kernel and shear butter oils	Cutting force	Ojolo et al. [28]
Turning	Mild steel, brass and aluminum	HSS	Palm kernel oil	Cutting force	Ojolo and Ohunakin [30]
Turning	AISI 1040 steel	Cemented carbide	SAE – 40 and coconut oil	Temperature,flank wear and surface roughness	Krishna et al. [31]
Drilling	AISI 316L steel	HSS tool	Rape seed oil and mineral oil	Tool life, cutting force and chip formation	Belluco and De Chiffre [32]
Drilling	AISI 304 steel	HSS- E	Sunflower oil and mineral oil	Surface roughness and thrust force	Kuram et al. [34]
Drilling	Titanium alloys (Ti-6Al-4 V	Carbide coated with AlTiN	Palm kernel oil and synthetic ester	Thrust force, torque and temperature	Rahim and Sasahara [44]
Grinding	SAE 1020 steel	Cubic Boron Nitride (CBN) tool	Vegetable oil and semi-synthetic oil	Wheel wear, workpiece roughness	Alves and Oliveira [45]
Grinding	100Cr6 steel	CBN	Mineral oil, rape seed oil, palm kernel oil, animal oil and cooking oil	Workpiece roughness, ecological and cost assessment	Hermmann et al. [46]
Milling	AISI 420 steel	Carbide-TiAIN and AIT	Palm kernel oil	Cutting force, tool life and surface roughness	Sharif et al. [47]
Milling	AISI 304 steel	HM90 APKT, 100304PDR IC908	Canola oil and sunflower oil	Tool wear and cutting force	Kuram et al. [43]

that sperm oil was superior to lard oil while cutting steel material [10]. It was also on record that vegetable and animal oils were used by the earlier men as source of cutting fluid before the discovery of petroleum in 1850s. It was this discovery of petroleum that saw the emerging of petroleum (mineral) oil as an alternative to vegetable oil, as based oil for MWFs. Between 1900 and till date, more researches were been reported about the application of vegetable-oil based MWFs in machining ferrous metals than both non-ferrous metals and super alloy materials put together as shown in Table 3. This gap in research development in the application of vegetable-oil based metalworking fluids during machining non-ferrous materials/super alloy materials demand urgent attention. The environmental impacts and governmental regulations on mineral (petroleum) oil-based MWFs; necessitate the need to revisit MWFs based on vegetable oil.

MWFs increase productivity and the quality of manufacturing operations by cooling and lubricating during metal forming and cutting processes [52], hence, it cannot be ignored in machining processes. Reports indicate that nearly 38 million metric tons of lubricants were used globally in 2005, with a projected increase of 1.2% for the next decade [53]. Due to their advantages, the consumption of MWFs is increasing in machining industry. It is reported that European Union alone consumes approximately 320,000 tonnes per year of MWFs of which, at least two-thirds need to be disposed [54]. Despite their widespread use, they pose significant health and environmental hazards throughout their life cycle because of their nature as petrol based cutting fluid. It was reported that about 80% of all occupational diseases of operators were due to skin contact with cutting fluids [55–59]. Estimation says that in the USA alone about 700,000 to one million workers are exposed to MWFs [60]. As cutting fluids are complex in their composition, they may be irritant or allergic. Even microbial toxins are generated by bacteria and fungi present, particularly in water-soluble cutting fluids [61], which are more 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. Approximately 85% of lubricants being used around the world are petroleum-based oils [62]. Enormous use of petroleum based oils, created many negative effects on environment. The major negative effects is particularly linked to their in approximate use, which results in surface water and groundwater contamination, air pollution, soil contamination and consequently, agricultural product and food contamination [63].

The growing demand for biodegradable materials has opened an avenue for using vegetable oils as an alternative to petroleum-based polymeric materials [64, 65], most especially in machining operations. The public awareness in environmental issues has been constantly growing [66]. Lubricants are used in many diverse areas; therefore, their environmental acceptability has become increasingly important. As a result, research on biodegradable functional fluids are emerging as one of the top priorities in lubrication in the early 1990s as a result, a lot of growing number of environmentally friendly fluids and lubricants now compete in the market [67]. Vegetable oils, especially rapeseed [68] and canola [69] 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 [70].

Many researchers [25, 27–32, 34, 35] have studied the application of vegetable-oil based MWFs and pointed to the fact that vegetable oil is an alternative source for MWFs in machining processes. Researchers like Belluco and De Chiffre [32] have studied the performance of vegetable-based oils in drilling AISI 316L austenitic stainless steel using conventional HSS-Co tools. They observed that the thrust force was significant for both the whole life span of the tool and the measurements obtained show a good performance throughout the tool life span and concluded from the experimental result that there were relative increases in tool life of 177% with the best fluid, whereas the decrease of cutting thrust was less than 7% and that all vegetable-oil based fluids performed better than the commercial mineral oil used as reference product. Sharif et al. [47], who 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 (TiA1N and A1TiN), observed that, tool wear progressed gradually 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. The highest tool life recorded was when palm oil was used, which was 160.27 min followed by fatty alcohol 137.74 min, flood 39.86 min and dry 35.16 min. To boost the study, the work of Rahim and Sasahara [44] comes handy as their work focused on one of the super alloy materials. They studied the potency of MQL palm oil (MQLPO) and MQL synthetic ester (MQLSE) during drilling of titanium alloys with carbide drill coated with AlTiN insert. They discovered that MQLPO exhibited comparable performance to the flood cutting condition in terms of maximum workpiece temperature as the two conditions recorded the lowest temperature in comparison to the MQLSE and air blow cutting conditions.

The selection of suitable cutting fluids in machining processes depends on three factors, which are (i) type of machining processes, (ii) type of workpiece material, (iii) type of cutting tool material [71–73]. The future research should focus on super alloy material with attention on the three mentioned factors to benefit maximally from the advantages that vegetable-oil based MWFs offers. Again, research focus on application of vegetable-oil based on grinding and milling processes especially milling process should be given serious attention to drive the benefit of vegetable-oil based metalworking fluids.

6. Conclusion

This review traced the historical background of MWFs with special focus on vegetable-oil based MWFs, highlighting the applications in different classes of metals. The authors observed that with the current trend in the emergence of different alloys of metals and the research gaps that exist in this direction, there is an urgent need to focus on research development in MWFs using vegetable oil as base material in machining processes. In order to derive the benefits vegetable-oil based MWFs offers, a study of its effect on these emerging alloy materials is crucial.

References

1. H.S. Abdalla, S. Patel, The performance and oxidation stability of sustainable metalworking fluid derived from vegetable extracts, Proc. ImechE Part B: J. Eng. Manuf., 220 (2006) 2027–2040.
2. J.S. McCoy, Introduction: Tracing the historical development of metalworking fluids, in: J.P. Byers (Ed.), Metalworking fluids, 2nd ed., CRC publishers, London, 2006, pp. 1–5.
3. J.A. Schey, Metal deformation processes: friction and lubrication, Marcel Dekker, New York, 1970, pp. 1–2.
4. www.pasvik_inari_net/neu/eng/history_early_metal_age.html, (18:18 GMT on 7th Dec, 2014)
5. www.pasvik_inari_net/neu/eng/history_late_metal_age.html, (18:30 GMT on 7th Dec, 2014)
6. D. Dowson, History of Tribology, Longmans Green, New York, 1979, pp. 177–178, 253.
7. R.S. Woodbury, History of the grinding machine, MIT press, Cambridge, MA, 1959, pp. 21–41.
8. J. Naysmyth, James Naysmyth: an autobiography, S. Stiles (Ed.), Harper and Brothers, London, 1883, p. 437.

9. W.H.A. Northcott, A treatise on Lathes and turning, Longmans Green and Company, London, 1868.
10. F.W. Taylor, On the art of cutting metals, Society of Mechanical Engineers, New York, 1907, pp. 138–143.
11. W.H. Oldacre, Cutting fluids and process of making the same, US Patent No. 1, 604, 068.
12. Lubrication, The Texas Oil Company, New York, Vol. 39, 1944, pp. 9–16.
13. R. Kelly, Carbide Tool Journal 117 (1985) 28.
14. H.W. Hutton, Process of producing water soluble oil, British Patent No. 13, 999, 1923.
15. H. Ernst, Physics of metal cutting; machining of metals, American Society of Metals, Cleveland, OH, 1938, pp. 1–34.
16. M.E. Merchant, J. Appl. Phys. 16 (1945) 267–275.
17. K.E. Bisshopp, E.F. Lype, S. Raynor, Lubric. Eng. 6 (1950) 70–74.
18. A.O. Schmidt, W.W. Gilbert, O.W. Boston, Trans. AMSE 164 (1942) 703–709.
19. A.O. Schmidt, G.B.V. Sirotkin, Lubric. Eng. 4 (1948) 251–256.
20. H. Ernst, M.E. Merchant, Surface treatment of metals, American Society of Metals, Clevelands, OH, 1948, pp. 299–337.
21. M.C. Shaw, Met. Program 42 (1942) 85–89.
22. M.C. Shaw J. Appl. Mech. 113 (1948) 37–44.
23. M.E. Merchant, Lubric. Eng. 6 (1950) 167–181.
24. B.H. Jennings, New products and equipment: water soluble emulsion, Lubric. Eng. 1 (1945) 79.
25. S.A. Lawal, I.A. Choudhury, Y. Nukman, Evaluation of vegetable and mineral oil-in-water emulsion cutting fluids in turning AISI 4340 steel with coated carbide tools, J. Clean. Prod. 66 (2014) 610–618.
26. M.A. Xavior, M. Adithan, Determining the influence of cutting fluids on tool wear and surface roughness during turning of AISI 304 austenitic stainless steel, J. Mater. Process. Technol. 20 (2009) 900–909.
27. M.M.A. Khan, M.A.H. Mithu, N.R. Dhar, Effects of minimum quantity lubrication on turning AISI 9310 alloy steel using vegetable oil-based cutting fluid, J. Mater. Process. Technol. 209 (2009) 5573–5583.
28. S.J. Ojolo, M.O.H. Amuda, O.Y. Ogunmola, C.U. Ononiwu, Experimental determination of the effect of some straight biological oils on cutting force during cylindrical turning, Revista Matéria 13 (2008) 650–663, http://www.materia.coppe.ufrj.br/sarra/artigos/artigo11007
29. S.A. Lawal, M.S. Abolarin, B.I. Ugheoke, E.O. Onche, Performance evaluation of cutting fluids developed from fixed oils, LEJPT 10 (2007) 137–144.
30. S.J. Ojolo, O.S. Ohunakin, Study of rake face action on cutting using palm-kernel oil as lubricant, JETEAS 2 (2011) 30–35, © Scholarlink Research Institute Journals, (ISSN: 2141-7016), http://www.jeteas.scholarlinkresearch.org
31. P.V. Krishna, R.R. Srikant, D.N. Rao, Experimental investigation on the performance of nanoboric acid suspensions in SAE-40 and coconut oil during turning of AISI 1040 steel, Int. J. Mach. Tool Manuf. 50 (2010) 911–916.
32. W. Belluco, L. De Chiffre, Performance evaluation of vegetable – based oils in drilling austenitic stainless steel, J. Mater. Process. Technol. 148 (2004) 171–176.
33. D.C. Montgomery, Design and analysis of experiments, 4th ed., Wiley, New York, 1997.
34. E. Kuram, B. Ozcelik, E. Demirbas, E. Sik, Effects of the cutting fluid types and cutting parameters on surface roughness and thrust force, Proceed WCE 2010, Vol. II, WCE 2010, London, UK, June 30–July 2, 2010.
35. E. Kuram, Investigation of vegetable-based cutting fluids performance in drilling M.Sc Thesis, Gebze Institute of Technology, Gebze Kocaeli Turkey, 2009 (in Turkish).
36. J.P. Davim, P.S. Sreejith, R. Gomes, C. Peixoto, Experimental studies on drilling of aluminium (AA1050) under dry, minimum quantity of lubricant, and flood-lubricated conditions, Proc. Inst. Mech. Eng. B: J. Eng. 220 (2006) 1605–1611.
37. S. Basavarajappa, G. Chandramohan, J.P. Davim, Some studies on drilling of hybrid metal matrix composites based on Taguchi techniques, J. Mater. Process. Technol. 196 (2008) 332–338.
38. M. Ramulu, P.N. Rao, H. Kao, Drilling of (Al2O3)p/6061 metal matrix composites, J. Mater. Process. Technol. 124 (2008) 244–254.
39. O.C. Mendes, R.F. Avila, A.M. Abrao, P. Reis, J.P. Davim, The performance of cutting fluids when machining aluminium alloys, Ind. Lubr. Tribol. 58 (2006) 260–268.
40. R. Shetty, R. Pai, S.S. Rao, Experimental studies on turning of discontinuously reinforced aluminium composites under dry, oil water emulsion and steam lubricated conditions using Taguchi's technique, G.U. J. Sci. 22 (2009) 21–32.
41. A. Rivero, G. Aramendi, S. Herranz, L.N. López de Lacalle, An experimental investigation of the effect of coatings and cutting parameters on the dry drilling performance of aluminium alloys, Int. J. Adv. Manuf. Technol. 28 (2006) 1–11.
42. C.C. Tsao, An experiment study of hard coating and cutting fluid effect in milling aluminum alloy, Int. J. Adv. Manuf. Technol. 32 (2007) 885–891.
43. E. Kuram, B.T. Simsek, B. Ozcelik, E. Demirbas, S. Askin, Optimization of the cutting fluids and parameters using Taguchi and ANOVA in milling, Proc. WCE 2010, Vol. II, WCE 2010, London, UK, June 30–July 2, 2010.
44. E.A. Rahim, H. Sasahara, A study of the effect of palm oil as MQL lubricant on high speed drilling of titanium alloys, Tribol. Int. 44 (2011) 309–317.
45. S.M. Alves, J.F.G. Oliveira, Development of new cutting fluid for grinding process adjusting mechanical performance and environmental impact, J. Mater. Process. Technol. 197 (2006) 185–189.
46. C. Herrmann, J. Hesselbach, R. Bock, T. Dettmer, Coolants made of native ester – technical, ecological and cost assessment from a life cycle perspective, Proceed of 14th CIRP Int. Conf. on Life Cycle Eng., Tokyo, Japan, 2007.
47. S. Sharif, N.M. Yusof, M.H. Idris, Z.B. Ahmad, I. Sudin, A. Ripin, M.A.H. Mat Zin, Feasibility study of using vegetable oil as a cutting lubricant through the use of minimum quantity lubrication during machining, Research VOT No. 78055, Department of Manufacturing and Industrial Engineering, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 2009, [eprints.utm.my/9729/1/78055.pdf]
48. W.F. Sales, A.E. Diniz, A.R. Machado, Application of cutting fluids in machining processes, J. Braz. Soc. Mech. Sci., Rio deJaneiro 23 (2001), doi: 10.1590/S0100-73862001000200009
49. I.A. Choudhury, M.A. El-Baradie, Machinability of nickel – base super alloys: a general review, J. Mater. Process. Technol. 77 (1998) 278–284.
50. K. Weinert, I. Inasaki, J. Sutherland, T. Wakabayashi, Dry machining and minimum lubrication, CIRP Ann.: Manuf. Technol. 53 (2004) 511–537.
51. C. Courbon, D. Kramar, P. Krajnik, F. Pusavec, J. Rech, J. Kopac, Investigation of machining performance in high – pressure

jet assisted turning of Inconel 718. An experimental study, Int. J. Mach. Tool Manuf. 49 (2009) 1114–1125.

52. Z. Julieb, F. Andres, H. Kimf, J. Steven, Design of hard water stable emulsifier systems for petroleum and bio-based semi-synthetic metalworking fluids, Environ. Sci. Technol. 37 (2003) 5278–5288.
53. Kline & Company, Inc., Competitive intelligence for the global lubricants industry, 2004–2014. Kline & Company, Inc., 2006.
54. H.S. Abdalla, W. Baines, G. McIntyre, C. Slade, Development of novel sustainable neat-oil metalworking fluids for stainless steel and titanium alloy machining. Part 1. Formulation development, J. Adv. Manuf. Technol. 34 (2007) 21–33.
55. E.O. Bennett, Water based cutting fluids and human health, Tribol. Int. 16 (1983) 133–136.
56. HSE, Health surveillance of occupational skin diseases, HSE Books, MS 24, London, 1991.
57. HSE, Medical aspects of occupational asthma, HSE Books, MS 25, London, 1991.
58. HSE, Health risks from metalworking fluids – aspects of good machine design, IND (G) 167L, HSE Books, London, 1994.
59. HSE, Metalworking fluids (MWFs) exposure assessment, EH74/4, HSE Books, London, 2000.
60. V.M. Korde, T.J. Phelps, P.R. Bienkowski, D.C. White, Biodegradation of chlorinated aliphatics and aromatic compounds in total-recycle expanded-bed reactors, Appl. Biochem. Biotechnol. 45/46 (1993) 731–740.
61. A. Zeman, A. Sprengel, D. Niedermeier, M. Spath, Biodegradable lubricants – studies on thermooxidation of metal – working fluids by differential scanning calorimetry (DSC), Thermoch. Acta 268 (1995) 9–15.
62. P. Loredana, P. Cosmina, B. Geza, V. Gabriela, N. Remus, Basestock oils for lubricants from mixtures of corn oil and synthetic diesters, J. Am. Oil Chem. Soc. 85 (2008) 71–76.
63. A. Birova, A. Pavloviova, J. Cvengro, Lubricating oils based on chemically modified vegetable oils, J. Synth. Lubr. 18 (2002) 291.
64. A.L. Bisio, M. Xanthos, How to manage plastics wastes, technology and market opportunities, Hanser Publishers, NY, 1995.
65. F. Li, M.V. Hanson, R.C. Larrock, Soybean oil-divinylbenzene thermosetting polymers, synthesis, structure, properties and their relationships, Polymer 42 (2001) 1567–1579.
66. H.F. Eichenberger, Biodegradable hydraulic lubricant – an overview of current developments in Central Europe. Paper No-910062, 1991.
67. C. Busch, W. Backe, Development and investigation in biodegradable hydraulic fluids, SAE Technical Paper 932450, SAE, Warrendale, PA, 1993.
68. F.J. Flider, Use of rapeseed oil in lubricants, INFORM 6 (1995) 1031–1035.
69. A.A. Wessol, Bill Whitacre, Operating hydraulics in "Green" fluids, Machine Design (Jan 22, 1993), pp. 73–77.
70. R. Gapinski, I. Joseph, B. Layzell, Vegetable oil based tractor lubricant, Off – Highway Engineering (December, 1994) 7–10.
71. M.A. El Baradie, Cutting fluids, Part I: Characterisation, J. Mater Process. Technol. 56 (1996) 786–797.
72. G. Avuncan, Machining economy and cutting tools, Makine Takim Endustrisi Ltd, Publication, Istanbul, 1998, pp. 375–403 (in Turkish).
73. I. Kavuncu, Cutting oils in metal machining, Turkish Chambers of Mechanical Engineers Publication, Istanbul (in Turkish).

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