Environmentally Friendly Machining: Vegetable Based Cutting Fluids

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Abstract A wide variety of cutting fluids are commercially available in the cutting fluid suppliers in order to provide machining performances for a number of industries. In machining, mineral, synthetic and semi-synthetic cutting fluids are widely used but, recently, uses of vegetable based cutting fluids have been increased. Although, these cutting fluids are beneficial in the industries, their uses are being questioned nowadays as regards to health and environmental issues. Cutting fluids are contaminated with metal particles and degradation products which diminish the effectiveness of cutting fluids. To minimize the adverse environmental effects associated with the use of cutting fluids, the hazardous components from their formulations have to be eliminated or reduced to the acceptable level. In addition, mineral based cutting fluids are going to be replaced with vegetable based cutting fluids since they are environmentally friendly. Today to diminish the negative effects associated with cutting fluids, researchers have developed new bio based cutting fluids from various vegetable oils. This chapter has also focused on environmental conscious machining such as dry cutting, machining with minimum quantity lubricant and especially machining with vegetable based cutting fluids including other types of cutting fluids. Literatures associated with types of cutting fluids have also been presented in this chapter.

1 Introduction

The use of lubricants in metal cutting operations is relatively recent as compared to the use of fats to grease chariot wheels to date back to the times of the ancient Egyptians. The widespread use of cutting fluids coincided with the industrial revolution in the late Eighteenth century. Mineral oils were being extensively used as

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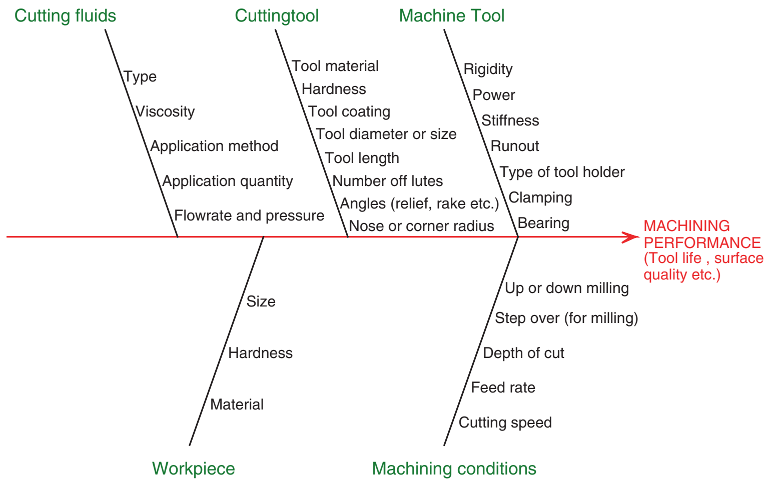

Fig. 1 Effect of machining parameters in performance

cutting fluids in the machining area by the mid-nineteenth century. In 1868, W.H. Northcott observed that the use of cutting fluids improved tool life. In 1883, Taylor used water in machining and demonstrated the importance of water as a cutting fluid and observed that cutting speeds could be increased by 30–40 % by using water.

The main aim of all machining operations is to obtain to lower machining costs by improving of quality and productivity. This aim can be achieved by machining at the highest cutting speed with long tool life, fewest part rejects (scrap) and minimum downtime. In machining, a lot of parameters affecting the cutting performances are shown in a fishbone (cause and effect) diagram (Fig. 1). Some machining operations can be carried out "dry", but cutting fluids have been used extensively and play a significant role in machining areas. Cutting fluids affect the productivity of machining operations, tool life, quality of workpiece and prevent the cutting tool and machine from overheating as well. The proper application of cutting fluid provides higher cutting speeds and higher feed rates possible. In general, a successful cutting fluid must not only improve the machining process performance, but also fulfil a number of requirements which are non-toxic, non-harmful to health for operators, not a fire hazard, not smoke or fog in use and cost less. One of the drawbacks of using cutting fluids is the waste disposal after being used.

Mineral based cutting fluids are reasonably priced so they are used extensively in machining area. But human beings were faced with mineral oil which was a limited resource due to the oil crisis of 1979 and 1983. Mineral oil has also poor biodegradability thus induces the potential for long term pollution of the environment. Moreover, the availability of mineral oil is highly dependent on political considerations. Therefore, existing deposits do not guarantee to us for the availability of mineral oil in the future [1]. The demand for biodegradable cutting fluids has increased with the use of vegetable based cutting fluids as an alternative to mineral based cutting fluids. Mineral based oils are limited and steadily decreasing resource whereas the vegetable based oils are sustainable.

2 Cutting Fluids

Classifications of cutting fluids are essential to understand them better since today a variety of cutting fluids are widely available in the world. According to chemical formulations, cutting fluids are classified into four categories: cutting oils, soluble oils (emulsified oils, emulsions), synthetic (chemical) fluids, semi-synthetic (semi-chemical) fluids. Cutting oils named as neat oil or straight cutting oil are formed oil derived from petroleum, animal or vegetable origin. Cutting oils used without further dilution in metal cutting processes have good lubrication properties, poor cooling properties and increases fire risk. They may also create a mist or smoke harmful to the health of operator. The use of cutting oils is limited to low temperature and low speed cutting operations.

Emulsified oils are a suspension of oil droplets in water. This cutting fluid is done by blending oil with emulsifier agent(s) to improve the stability of the emulsion in water. The general compositions of water based cutting fluids are as follows:

$$Base\ oil\ +\ Emulsifier\ +\ Other\ additives$$

$$Base\ oil \begin{cases} mineral\ oil \\ vegetable\ oil \end{cases}$$

$$Other\ additives \begin{cases} Neutralization\ agents \\ Corrosion\ and\ rust\ inhibitors \\ Lubricating\ additives\ \ (antiwear\ and\ EP\ additives) \\ Biocidies\ and\ \ fungicides \\ Foam\ inhibitors \end{cases}$$

Emulsifiers have the function of dispersing the oil in water in order to make a stable oil-in-water emulsion. Rao and Srikant [2] stated that thermal conductivity, kinematic viscosity and pH increased with an increase in the content of emulsifier whereas flash and fire points decreased with an increase in the amount of emulsifier. In turning of AISI 1040 steel decrements of cutting forces, surface roughness and tool wear with an increase in the emulsifier content were found by Srikant et al. [3]. Higher heat transfer rates, higher hardness and lesser surface roughness were observed in cutting fluids with higher rate of emulsifier content [4].

The concentrate cutting fluids must be stable without separating for a minimum of six months storage and emulsion stability is the most critical property of soluble oils. The presence of water in emulsions induces rust, bacterial growth and evaporation losses. Sulphur, chlorine and phosphorous based chemical additives known as extreme pressure (EP) additives are used under extreme pressure conditions. EP additives form solid lubricant layer between cutting fluid and the metal surface by chemical reaction. This film possesses low shear strength and good antiweld properties so EP additives can reduce friction and wear effectively. Emulsions have some advantages:

- reduction of heat allows higher cutting speeds in machining.
- dilution with water to cut the cost.
- no fire hazard and a lower rate of oil misting.

One of the drawbacks associated with emulsions is the fungi and bacteria growth which increases health hazards and diminishes the service life of cutting fluids. Presence of bacteria in the cutting fluid can cause separation in the emulsions. As a result the coolant lubricity capability is degraded by the bacteria. Moreover, pH of the coolant can help to reduce corrosion of workpiece and machine tool, and influences the microbial activity [5]. Germicide and bactericide additives are added to emulsions to control the bacteria growth.

In order to control bacterial growth in cutting fluids, chemical additives are necessary but they are hazardous for both the environment and health of operators [5]. Antimicrobials and biocides are utilized to maintain the efficiency of cutting fluids rather than protecting the operators. Formaldehyde releasing biocides are potential carcinogenic. Some of lubricants in the cutting fluids is considered to be hazardous to the environment and health [6] such as chlorinated extreme pressure additives.

Synthetic and semi-synthetic cutting fluids are mentioned in Sect. 2.2. Advantages and disadvantages of different types of cutting fluids are presented in Table 1.

Cutting fluids are applied to the cutting region in order to improve the cutting performance. The primary function of cutting fluid is to reduce temperature generated at cutting tool/workpiece interface. The hardness and resistance to abrasion of cutting tools are reduced at high temperature. Temperatures generated during machining affect the tool wear. So the reduction of this temperature will cause extending tool life. Cutting fluids also cool the workpiece, thus preventing its final dimensions. Cutting fluids' cooling of workpiece function is very important especially in grinding operations. The reduction temperatures ability of a cutting fluid during machining depends on its thermal properties especially specific heat and thermal conductivity. The other function of cutting fluid is lubrication. Lubrication effect of cutting fluids minimizes the amount of heat generated by friction. Cutting fluids with high lubricant ability are generally used in low-speed machining such as screw cutting, broaching and gear cutting and on difficult-to-cut materials, whereas cutting fluids with high cooling ability are generally used in high-speed machining [7].

Table 1 Advantages and disadvantages of cutting fluids

Straight oils	Soluble oils	Semi-synthetics	Synthetics
Advantages			
Excellent lubricity	Good lubricity	Good cooling	Excellent cooling
Excellent rust control	Good cooling	Good rust control	Excellent microbial control
		Good microbial control	Nonflammable, nonsmoking
			Good corrosion control
			Reduced misting and foaming problems
Disadvantages			
Low cooling	Rust control problems	Foam easily	Poor lubricity
Fire hazard	Bacterial growth	Stability is affected by water hardness	Easily contaminated by other machine fluids
Create a mist or smoke	Evaporation losses	Easily contaminated by other machine fluids	
Limited to low-speed and heavy cutting operations			

Cooling effect can be done best by water with low cost but its lubrication properties are very low. Water possesses high specific heat and thermal conductivity and this is the reason why water is used as the base in cutting fluids. Besides, water is cheap, supplied easily and its low viscosity provides it to flow at high rates. However, it causes some corrosion at ferrous metals and this may be diminished with corrosion inhibitors.

Cutting fluids consist of base oil(s), emulsifiers, corrosion inhibitors, lubricating, anti-wear and high pressure additives, neutralizing agents, biocides, fungicides, foam inhibitors and stabilizing agents to obtain favourable properties and to diminish the harmful effects.

The chemical additives used to formulate cutting fluids provide various functions such as emulsification, corrosion inhibition, lubrication, microbial control, defoaming, dispersing and wetting. Most of the additives used are organic chemicals that are anionic or nonionic in charge and most of the additives are liquids in order to blend easy. Some of the chemical additive types used are fatty acids, esters, sulfonates, soaps, chlorinated paraffins and fatty oils.

Cutting fluids also remove chips from tool/workpiece interface to prevent a finished surface. Especially at higher cutting speeds and feed rates, greater amounts of chips are generated in machining. Hence removal of chips from cutting area at these situations is very significant function of cutting fluids. The cutting fluid capability of flushing away the chips from the cutting zone depends on mainly its viscosity and flow rate. Viscosity is the resistance to flow of oil and is affected inversely by temperature. The tendency of the viscosity of oil with temperature changes is called *viscosity index* (V.I). A low V.I. signifies a relatively large change of viscosity with changes of temperature. In other words, the oil becomes extremely thin at high temperatures and extremely thick at low temperatures. A high V.I. means relatively little change in viscosity over a wide temperature range.

Cutting fluids reduce the adhesion of the workpiece to the cutting tool (reduce to form the built up edge (BUE) on the cutting tool), protect the workpiece and cutting tool surfaces from corrosion and lower the power required to machine (decreases friction). This shows both energy saving and less heat generating. If less heat is generated during machining, tool life of the cutting tools is longer and surface integrity of the workpiece is improved. Overall, the machining process will tend to be more stable.

Cutting fluids should have the following properties to fulfill their functions properly:

- Good lubricating properties
- High cooling capacity
- Low viscosity to provide free flow of cutting fluid
- Chemically stable
- Non-corrosive
- High flash point to reduce fire risks
- Allergy free
- Less evaporative
- Low cost

The selection of appropriate cutting fluid is very important because it could affect machining performance (tool life, cutting forces, surface roughness, power consumption etc.) and the selection depends on some parameters such as workpiece material used, cutting tool material and type of machining process. For instance, cutting fluids containing sulfur and chlorine additives should not be used with nickel-based alloys and titanium, respectively. Cutting fluids with high lubricity ability are generally used in low-speed machining such as screw cutting, broaching and gear cutting and on difficult-to-cut materials, whereas cutting fluids with high cooling ability are generally used in high-speed machining.

2.1 Mineral Based Cutting Fluids

Mineral based cutting fluids consist of oils extracted from petroleum. Mineral oils are hydrocarbons and their properties base on the chain length, structure and refining level. Two types of mineral oil are used in metal cutting fluids: Paraffinic and naphthenic. Paraffinic oils consist of long linear chains of hydrogen and carbon atoms. Naphthenic oils behave differently from paraffinic oils due to the molecular structure with hydrocarbons rings. Mineral oil has poor biodegradability thus it induces the potential for long term pollution of the environment. Mineral based oil is also a limited and steadily decreasing resource.

2.2 Semi-Synthetic and Synthetic Cutting Fluids

Synthetic and semi-synthetic cutting fluids are blended with water and various chemical agents. These agents are added for rust prevention, lubrication and reduction of surface tension. Synthetic cutting fluids have good coolant properties but their lubricant properties are less than the other cutting fluid types. Since synthetic cutting fluids are transparent, they help the operator to monitor the machining process. Synthetic cutting fluids are generally more resistant to biological attack than emulsions. Semi-synthetic cutting fluids are combinations of synthetic cutting fluids and emulsions. Semi-synthetic cutting fluids contain less oil (2–30 % oil) whereas synthetic cutting fluids contain no oil.

2.3 Vegetable Based Cutting Fluids

Vegetable oils consist of triacylglycerides (triglycerides) which are glycerol molecules 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. But their unsaturation levels vary. The triglyceride structure of vegetable oils provides desirable properties of lubricant. Long, polar fatty acid chains provide high strength lubricant films which interact strongly with metallic surfaces and reduces both friction and wear [8]. Vegetable oils have a higher viscosity index. However, thermal and oxidation stability of vegetable oils are limited [9]. Vegetable oils perform better than the other oils and the reasons are described as follow:

- Vegetable oils have good lubricity properties. The highly lubricating properties of vegetable oil are made possible by the fundamental composition of the vegetable oil molecules, as well as the chemical structure of the oil itself. Its properties are the direct result of the vegetable oil's smart molecules. These molecules are long, heavy, and dipolar in nature; that is, the ends of the molecules have opposing electrical charges [10]. Vegetable oils carry slight polar charge but mineral oils have no charge. This polar charge draws the vegetable oil molecule to a metallic surface like little magnets; therefore, vegetable oils adhere to a metal surface more tightly than mineral oils [10, 11]. Dense, homogeneous alignment of vegetable oil molecules creates a thick, strong and durable film layer of lubricant. This lubricating film gives the vegetable oil a greater

capacity to absorb pressure. In contrast, the molecules of mineral oils are intrinsically non-polar. They form a random alignment along a metal surface, which provides a weaker layer of lubrication [10]. Consequently, vegetable oils make a better lubricant [11].
- Vegetable oils have a higher flash point, which reduce smoke formation and fire hazard [10, 11]. Higher flash point value allows using the cutting fluid in high temperature conditions.
- Viscosity is another oil property that has an important effect on machining productivity [10]. Vegetable oils have a high natural viscosity as the machining temperature increases. The viscosity of vegetable oils drops more slowly than that of mineral oils. As the temperature falls, vegetable oils remain more fluid than mineral oils, facilitating quicker drainage from chips and workpieces. The higher viscosity index of vegetable oils ensures that vegetable oils will provide more stable lubricity across the operating temperature range [11].
- Vegetable oil molecules are quite homogeneous in size but mineral oil molecules vary in size. Consequently, the properties of mineral oil such as viscosity, boiling temperature are more susceptible to variation [10].
- Vegetable oil has higher boiling point and greater molecular weight and this results in less loss from vaporization and misting [12].

3 Environmental Aspects of Cutting Fluids

The use of cutting fluids repeatedly over time induces chemical changes of cutting fluids. These changes are due to the environmental effects, contamination from metal chips and tramp oil. The growth of bacteria and yeast becomes environmental hazard and also adversely affects the effectiveness of the cutting fluids. Cutting fluids degrade in quality with use and time and when they lose their quality the disposal of them is mandatory. Waste disposal of cutting fluids are expensive and affect the environment negatively.

The focus on lubricants has shifted from biodegradability to renewability over the years and owing to the change in human beings' environmental thinking [13]. Several aspects of an environmentally adapted lubricant are as follows [14, 15]:

- Biodegradability
- Toxicity
- Renewability
- Bioaccumulability and biomagnifications
- Life cycle assessment (LCA)
- Energy saving and fuel economy

Biodegradability is the degradation by the action of micro organisms [15]. Environmental compatibility of cutting fluids is determined mostly with biodegradability [16]. Alves and Oliveira [17] conducted a biodegradation test in dark

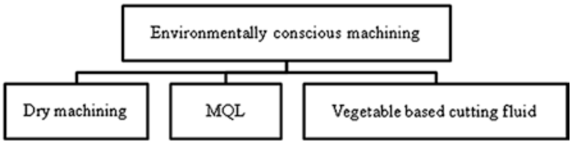

Fig. 2 Environmentally conscious machining

at 20–25 °C for 28 days for a new cutting fluid from castor oil. This cutting fluid showed high degradation rates and under these conditions mineral oil were degraded to 20–60 % hence mineral oil was not regarded as readily biodegradable. In an another work, it was found that vegetable based synthetic ester and rapeseed oil had 100 % biodegradable, whereas neat type of cutting oil had 20–30 % biodegradable [18]. Bioaccumulation is a substance accumulation in an organism. Biomagnification is to increase the concentration of accumulated substance in the food chain [14]. Renewability is the relative amount in any given product of raw material that can be re-grown, recycled or re-used [15].

Cutting fluids affect the health of operator negatively in machining operations which can be vaporised, atomised and form mist owing to high pressure and temperature. This airborne particle of cutting fluids can be inhaled by operators and causes mild respiratory problems, asthma and several types of cancers (oesophagus, stomach, pancreas, colon, etc.) [6]. Mist, fumes, smoke and odors can cause severe skin reactions and respiratory problems. When physical contact with cutting fluid occurs, dermatological problems are seen in operators. Cutting fluids also may influence adversely the machine tool components which should be cleaned to remove any cutting fluid residue. This cleaning operation requires additional time and cost. Water based and low viscosity cutting fluids can be preferred in order to ease of cleaning.

Cutting fluids used in machining area contain environmentally harmful chemical substances. These chemicals have negative effect on the environment and human health as well. Most of the cutting fluids used in machining are petroleum origin and the disposal of petroleum-based cutting fluids causes water contamination, air and soil pollutions. Dry cutting, machining with minimum quantity lubricant (MQL) and vegetable based cutting fluids are believed as environmental conscious machining (Fig. 2).

4 Application Methods for Cutting Fluids

Cutting fluids can be applied to a cutting tool/workpiece interface by some methods such as manual, flooding and mist application. For efficient machining performance, a lubricant film must be formed at the sliding surface. For better performance, application of cutting fluid to the cutting zone must be continuous, not intermittent. Unless cutting fluid is carefully placed, it cannot perform its cooling and lubrication functions effectively.

In manual application, operator uses oil container to apply cutting fluid to the cutting region. This is the easiest and the cheapest method of cutting fluid application; however it has limited use in machining area. Manual method is intermittent cutting fluid application so its performance is low compared to continuous application methods. Access of cutting fluid to the cutting region is limited in this application.

Flooding is the most common application method of cutting fluids to the tool/workpiece interface. In flooding application, large quantity of cutting fluid is continuously delivered to the cutting region by means of a pipe, hose or nozzle. The cutting fluid is cumulated in a reservoir, filtered and pumped back to the delivery nozzle in this method. In order to obtain optimum machining performance, direction of nozzle, number of nozzles and flow rate of cutting fluids must be optimized. At some situation cutting fluid is not able to reach cutting zone effectively.

In mist application, cutting fluids are atomized and blown onto cutting tool/workpiece interface. This method is not as effective as flooding to cool the cutting tool; however it may sometimes be more effective than flooding such as delivering the cutting fluids to cutting zone that are difficult to access by flooding. However, inhalation of mist by the operator induces health problems so very efficient ventilation is required.

Cutting fluids can be applied to cutting region three possible directions as shown in Fig. 3.

- on the back side of the chip,
- along between the chip and rake face of the cutting tool,
- along between the finished workpiece surface and flank face of the cutting tool [19].

Mendes et al. [20] investigated the performance of cutting fluids in the drilling of AA 1050-O aluminium and applied cutting fluid as a mist. They also investigated

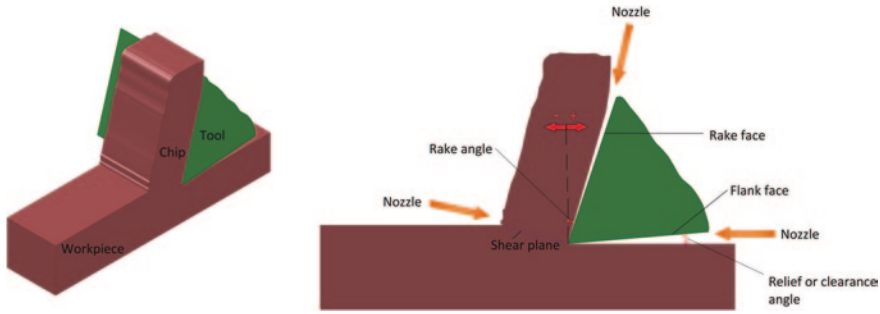

Fig. 3 Application directions of cutting fluids in orthogonal cutting

the effect of additives (chlorine, sulphur and phosphor) on the performance of the cutting fluid applied as a flood in the turning of 6262-T6 aluminium alloy. In drilling, 100 ml/h flow rate resulted in lower feed forces especially at higher cutting speeds and feed rates. In contrast to the feed force results, increment in the cutting flow rate in general resulted in higher torque, power consumption and specific cutting pressure. Surface roughness was not significantly affected by cutting fluid flow rate in the drilling. In general, an increment of the cutting fluid concentration showed a decrement of the cutting force, but this decrement was nearly negligible when comparing concentrations of 10 and 15 % in the turning. Three directions of cutting fluid application were compared: (1) over the chip and rake face, (2) at the tool-chip interface and (3) at the tool-workpiece interface. When cutting fluid was applied over the chip and rake face, considerably higher forces were observed. Experimental turning study was also carried out in which the cutting fluid concentration (10 %) was kept constant as well as the direction of cutting fluid application (at the tool-workpiece interface) so that compared the effect of EP additives (chlorine, sulphur and phosphor). The lowest cutting force was achieved using the cutting fluid with chlorine additive followed by the cutting fluid with sulphur additive. The best surface finish was obtained using the cutting fluid with chlorine additive.

Especially in drilling the use of cutting fluids under high pressures (pressurized jets) via internal holes in drills can improve lubrication, cooling and chip removal. The cutting fluid is fed through internal holes to the cutting region. In high-pressure cutting fluids, greater penetration of the cutting fluid into the tool-chip interface occurs as compared to the flooding application. Machado et al. [21] found that using high pressure cooling when turning of Ti6Al4V increased tool life up to 300 % as compared to conventional flood application and lower tool life was achieved when machining Inconel 901 under the high pressure coolant jet. Kaminski and Alvelid [22] proved that when applying high-pressure coolant at 250 bar, the cutting temperature could be reduced by ~40 % compared to flood application and further increment in pressure had minimal additional effect. Ezugwu and Bonney [23] found that acceptable surface finish and improved tool life can be obtained during machining of Inconel 718 with high coolant pressures. When machining at 203 bar coolant pressure at a cutting speed of 50 m/min, tool life increased 740 % as compared to conventional coolant application. In general, increment in tool life was observed with increasing coolant pressure. In another study, Ezugwu and Bonney [24] carried out the turning experiments of Inconel 718 alloy under conventional and high-pressure (11, 15 and 20.3 MPa) coolant supplies. Tool life, surface roughness and force components were measured and it was concluded that acceptable surface finish and improved tool life could be achieved when machining with high coolant pressures. The highest improvement in tool life (349 %) was obtained when turning with 11 MPa coolant pressure at higher cutting speed of 60 m/min. Machining with coolant pressures in excess of 11 MPa at cutting speeds up to 40 m/min decreased tool life more than machining with conventional coolant flow. This result showed that there was a critical coolant pressure which the cutting tools performed better under high-pressure coolant supplies.

However, in milling of En32b low carbon steel, flood coolant gave lower flank wear than high-pressure (1.8 MPa) environment [25]. Effect of fluid pressure, flow rate and direction of application in finish turning of AISI 1045 steel were investigated. When cutting fluid was applied to the tool rake face, the adhesion between chip and tool was very strong, causing the removal of tool particles and large crater wear. When cutting fluid was not applied to the rake face, adhesion of chip material to the face occurred, but was not strong enough to remove tool particles as it moved across the face, and thus crater wear did not increase [26]. The effects of ultra-high pressure coolant on the surface integrity and tool life were investigated during finish turning of Inconel 718. Conventional flood cooling and ultra-high pressure coolant were supplied at 5 bar and from 70 to 450 bar, respectively. Also the effects of applying ultra-high pressure coolant to the rake face alone, flank face alone and both positions together were investigated. Applying ultra-high pressure coolant to the rake face of the tool (rake only) decreased the tool life with an increment in pressure; however this was not observed when the cutting fluid was applied at the flank face of the tool (flank only) or at both the flank and rake faces of the tool simultaneously (flank and rake). When the high-pressure jet was applied to the flank face, flank wear decreased but the notching was not affected. When using up to 450 bar pressure, no increment in tool life was seen. The results also showed that the level of workpiece microstructural deformation or surface roughness obtained when machining with either new or worn tools were not affected beneficial or detrimental by the application of ultra-high pressure coolant. Cutting fluid pressure and direction had relatively little effect on the level of surface integrity [27]. Machining experiments were conducted under conventional wet, high-pressure neat oil and high-pressure water soluble oil environments during turning of Ti-6Al-4V. High-pressure neat oil environment provided longest tool life [28].

5 Minimising Adverse Environmental Effects of Cutting Fluids

Environmental concerns, market forces and legislative requirements make imperative a search for new solutions that minimize environmental impact [29]. To minimise the adverse environmental effects associated with the use of cutting fluids, the best solution is to remove the hazardous components from their formulation. But we focused on alternative methods rather than formulation. The effective way of minimising adverse environmental effects from the use of cutting fluids is to minimise the volumes used and replace mineral based cutting fluids with environmentally friendly cutting fluids such as vegetable based cutting fluids. From an environmental point of view, the best method is dry machining. Dry machining not only reduces the contamination of water and air but also reduces danger to health of the operator. However, dry machining is not efficient for many cutting operations. In this case, minimum quantity lubricant (MQL) can be penetrated into the cutting zone so that improve machinability. MQL reduces the cutting fluid consumption but this method uses cutting fluids in the form of mist which increases health hazards for the operators [30]. Waste treatment costs, negative environmental effects and health hazards of petroleum based cutting fluids increase the requirement for renewable and biodegradable lubricants and vegetable based cutting fluids have a higher potential of use under these limitations [31]. Vegetable based cutting fluids can be considered environmentally friendly since these fluids are renewable and have high levels of biodegradability.

5.1 Dry Machining

Dry machining means that no cutting fluid is used during process. For economic as well as environmental reasons machining process is carried out without any cutting fluid but dry machining has some disadvantages. During dry machining process, temperature of the cutting tool is very high and this induces excessive tool wear thus decreasing tool life. Also the chips generated at machining cannot wash away and these chips cause deterioration on the machined surface.

The problems of cutting fluid contamination and disposal are not seen in dry machining. Dry machining does not induce the pollution of atmosphere or water resources. Contrary to dry machining in wet machining (machining with cutting fluids by any means flooding and MQL), environment, water source and soil become polluted during disposal of the cutting fluid. Application of machining with dry will also diminish the manufacturing costs.

In some cases for instance in interrupted machining process like milling, dry cutting gives longer tool life than machining with cutting fluid. In milling cutting tool does not cut continuously and the using of cutting fluids increase thermal shock effect. Hence, dry machining is better suited for milling operations. In addition machining with ceramic tools must be conducted in dry condition due to the thermal shock. In drilling especially gun drilling the most important function of cutting fluid is the chip removal and dry cutting may induce drill breakage.

Dry cutting shows positive effects in some workpiece materials such as AISI 316 stainless steel [32]. Diniz et al. [33] used two concentrations (7 and 12 %) of the vegetable oil based emulsion with two different ways of fluid application (internally and externally to the tool) in the milling of 15-5PH stainless steel and the tool life results were compared to the dry cutting. Tool life for dry cutting was 3.5 times higher than those obtained when abundant fluid was utilized. It was found that the way of fluid application did not influence tool life.

However, in some workpiece materials dry machining presents many problems. For instance, aluminium is a soft material and dry machining of aluminium induces BUE. This influences on the surface quality of the workpiece.

Higher friction between tool and workpiece in dry machining can increase the temperature in cutting region. This high temperature will cause dimensional inaccuracies at the workpiece and excessive tool wear. So the disadvantages of dry machining have to be compensated. Improving cutting tools properties by better tool materials with lower friction coefficient and high heat resistance, coatings or tool geometries are investigated by researchers in order to compensate the effects of the elimination of cutting fluids in machining.

In order to make the application of dry machining feasible, some attempts have been done by the researchers. One of these attempts is to use tool materials with coating. In dry machining, advanced cutting tool materials and selection of cutting parameters are inevitable; however these cutting tools are very expensive and increase the machining costs [6].

Diniz and Micaroni [34] carried out turning experiments of AISI 1045 steel at varying cutting speed, feed and tool nose radius in order to obtain cutting conditions more suitable for dry cutting which make tool life closer to cutting fluid conditions without damaging the workpiece surface roughness and not increasing cutting power consumed by the process. To reach these aims it was mandatory to increase feed and tool nose radius and decrease cutting speed when cutting fluids are removed from a turning process. The use of cutting fluids gave longer tool life than dry cutting but difference in tool life between wet and dry cutting reduced at higher feed values. Dry cutting also showed less power and surface roughness than wet cutting. The increment of tool nose radius increased tool life and cutting power.

5.2 Machining with Minimum Quantity of Lubrication

In MQL method, a small amount of cutting fluid (10–100 ml/h) with compressed air is applied to the chip-tool interface to lubricate the contact area of chip-tool, to reduce temperature and friction. MQL can reduce the cost associated with the disposal of waste oils and the cutting fluid cost, whereas carrying chips away from cutting regions is limited.

In MQL; chip, workpiece and tool holder have a low residue of lubricant thus their cleaning is easier and cheaper as compared to flooding of cutting fluid. The cutting region is not flooded in MQL during machining so the operation can be seen by the operator [35]. MQL is used as a lubricating method rather than cooling. This poor cooling capacity limits the effectiveness of MQL in machining of difficult-to-machine materials such as titanium and nickel based alloys due to the excessive heat generation [36]. Thus in machining these pros and cons must be taken into consideration. The cutting performance of MQL mainly depends on nozzle pressure, number of pulses and amount of cutting fluid in each pulse so it is possible to produce high quality components with MQL by carefully choosing these parameters [37].

Since the negative effects associated with the cutting fluids, a lot of study has been concentrated on minimizing the use of cutting fluids or to eliminate cutting fluids in machining. Several experimental studies have investigated for the performance of MQL in the drilling [38–45], turning [46–51], milling [52–57] and grinding [58–61] processes. The most literature studies compared the performance of MQL with dry cutting and flood application. Conflicting results were found in the literature regarding the effect of different cutting fluid application methods (dry, MQL, flood) on cutting performance.

Kelly and Cotterell [38] used vegetable oil as MQL lubricant during drilling of cast aluminium silicon alloys. They concluded that the location of the feed nozzle, volume flow and pressure of the cutting fluid could be optimized in order to achieve longer tool life. Braga et al. [39] used MQL technique in the drilling of aluminium–silicon alloys. Zeilmann and Weingaertner [40] investigated the temperature during drilling of Ti6Al4V with MQL and it was found that internal MQL gave the lower temperature than external MQL. Davim et al. [29] reported experimental results of dry, MQL and flood-lubricated conditions during drilling of AA1050 aluminium. The cutting power and specific cutting force were higher for dry drilling but MQL and flood-lubricated conditions did not show much variation. MQL and flood-lubricated conditions gave similar surface finish results. A proper selection of the range of cutting parameters gave similar performances to flood-lubricated conditions by using MQL. Heinemann et al. [41] investigated the effects of MQL and dry cutting on the tool life in drilling of plain carbon steel. A discontinuous supply of the MQL showed a significant reduction in tool life as compared to a continuous supply of the MQL. It was also concluded that a low-viscous type with a high cooling capability type of MQL prolonged tool life. Tasdelen et al. [42] evaluated the effect of MQL, emulsion and air cooling on tool wear, surface finish and cutting forces during drilling of hardened steel. The lowest force and tool wear were obtained with emulsion and MQL, respectively. Costa et al. [43] studied the height of the burr under dry machining, MQL at the flow rate of 30 ml/h and conventional way (flooding) in the drilling. Vegetable oil in MQL, mineral oil in MQL and flooding and semi-synthetic oil in flooding were used as a cutting fluid. The smallest burr height was obtained for the dry drilling and the largest for the MQL systems. It was found in the literature that surface roughness, torque, force and tool wear of MQL drilling of austempered ductile iron were lower than that of dry drilling but higher than flooding [45].

Low quantity of cutting fluid is applied as a mist application in the most literature [38, 62, 63]. However, applying cutting fluid in the form of mist poses serious health hazards such as irritation, respiratory problems. Varadarajan et al. [46] introduced a new minimal cutting fluid application technique which diminished the problems caused by mist application during hard turning of hardened tool steel (AISI 4340). In this new method, a small quantity of cutting fluid was applied in the form of a high-velocity, narrow, pulsed jet. The rate of injection of cutting fluid, the injection and pulsing rate were 2 ml/min, 20 MPa and 600 pulse/min, respectively.

Dry and MQL conditions gave always smaller flank wear and surface roughness values than the wet cutting in the turning of SAE 52100 hardened steel [47]. Khan and Dhar [12] investigated the effect of MQL by vegetable oil on cutting temperature, tool wear, surface roughness and dimensional deviation in turning of AISI 1060 steel. MQL reduced the cutting temperature, tool wear and surface roughness as compared to dry machining. In turning of normalized 100Cr6 steel when MQL is applied to the tool rake, tool life is generally no different from dry cutting; however MQL applied to the tool flank can increase tool life [35]. Kamata and Obikawa [49] used dry, wet and MQL conditions during finish-turning of Inconel 718. The longest tool life was achieved with wet cutting but the surface finish was not good. It was also found that there is the optimum air pressure in finish-turning of Inconel 718 with MQL. Sreejith [50] analyzed the effect of dry machining, MQL and flooded coolant conditions with respect to the cutting forces, surface roughness and tool wear in turning of 6061 aluminium alloy. In MQL, the amount of material adhered was observed to be more compared with flooded and less compared with dry condition. It was not seen any considerable reduction in the adhered material, as the quantity of the lubricant was increased from 50 to 100 ml/h in MQL. The flank wear was seen to be almost same with MQL and flooded application. The lowest and highest resultant forces were achieved with flooded application and dry machining, respectively. For improving the quality of the workpiece surface, it was found that flooded coolant application was essential. Flood application of cutting fluid gave the lowest wear among the other application methods (MQL, MQL_EP and dry) during turning of AISI 1045 steel [51].

The efficiency of MQL was investigated in high speed milling of wrought aluminium alloys and was compared to emulsion. The effect of the position of the injection nozzle in relation to the feed direction was also studied. The nozzles were located at 45 and 135° in relation to the feed direction. In MQL, oil consumption was fixed at two values: 0.06 and 0.04 cm^3/min. Flank wear with MQL was always smaller than flank wear with the emulsion. The optimum nozzle-feed position was 135° considering tool life. Oil consumption below 0.06 cm^3/min showed a small increase of flank wear, but it was not very significant [52]. The amount of lubricant used in the study was much lower than that mentioned in most other studies [38, 46, 48, 64]. The study done by López de Lacalle et al. [52] not only improved tool life but also reduced the consumption of cutting fluids by 95 %.

Flank wear results showed that 6 ml/h was the best choice for the oil quantity among the others (6, 12 and 24 ml/h). P20 tool steels were milled with MQL at an oil volume of 6 ml/h and the distance between the nozzle and the tool tip was varied. When the nozzle was placed 60 mm away from the tool tip, the flank wear reached the maximum value. The flank wear was low and almost constant when the distance was between 80 and 200 mm. An appropriate oil quantity and distance between the nozzle and tool tip provide the optimum process condition in MQL [53]. The performance of minimal cutting fluid application in pulsed-jet form in the high-speed milling of hardened steel was investigated [55]. Flank wear in pulsed-jet application was lower than in flood application and dry cutting, especially at high cutting speed and/or low feed rate. The performance of pulsed-jet application was superior to that of flood application and dry cutting in terms of surface finish. Experiments were also conducted until tool failure so that investigate the progression of cutting force, surface roughness and flank wear against cutting time at constant machining parameters. Cutting forces in pulsed-jet application were lower than in flood application and dry cutting considering the whole period of machining. Increment of flank wear in pulsed-jet application was slow at the beginning and after 50 min machining flank wear increased at a higher rate. Whereas, increment of flank wear in flood application and dry cutting was rapid at the beginning and after around 30 min, rate of flank wear became slower. When tool life criterion was set at 0.35 mm of flank wear, tool life of all applications was found to be almost the same. Lowest surface roughness values were achieved with pulsed-jet application. They stated that the lubricity of cutting fluid had a dominant effect on tool wear rather than cooling. They also said that in flood application, cutting fluid may not be able to access the tool-chip interface owing to the low pressure of flood application. Sales et al. [56] evaluated tool wear, surface roughness and burr formation when milling AISI 4140 steel with cutting fluid applied by MQL technique. The vegetable based cutting fluid and different flow rate (dry cutting, 50, 100, 150 and 200 ml/h) were used. Increment in coolant flow rate tended to reduce tool wear, surface roughness and burr length.

MQL flank face cooling showed longer tool life and lower surface roughness as compared to dry and MQL rake face application since the cutting fluid could not reach the tool-chip interface during application of cutting fluid on the rake face [64].

The overall performance (cutting force, tool life, surface finish, cutting ratio, cutting temperature and tool-chip contact length) during MQL was found to be superior to dry and conventional wet turning of hardened steel [65]. Obikawa et al. [66] investigated the performance of MQL in high-speed grooving of carbon steel. It was found that tool wears reduced in MQL more effectively than the solution type cutting fluid. The tool wears decreased drastically with the increment the pressure of air supply.

Tawakoli et al. [58] investigated the MQL technique in grinding of a 100Cr6 hardened steel and a 42CrMo4 soft steel. Grinding forces and surface quality were measured under different environments (dry, MQL, fluid). The surface finish in grinding of 100Cr6 hardened steel was significantly better when MQL technique was used. However, in grinding of 42CrMo4 soft steel with MQL, the surface roughness was found to be higher than that in fluid application. MQL grinding gave lower tangential forces than both dry and fluid application. Hadad et al. [60] found in MQL higher temperature than that in fluid application during grinding of 100Cr6 (AISI 52100) steel. Mao et al. [61] investigated the grinding performance of AISI 52100 steel with respect to grinding force, temperature and surface integrity of workpiece under the different cooling-lubrication conditions (wet, dry, pure oil MQL and oil–water MQL). The lowest grinding force was obtained under wet condition, while dry grinding gave highest force. Pure oil MQL grinding had slightly lower tangential force than that of oil–water MQL. Surface roughness results were similar to force results. Wet grinding had the lowest temperature and dry grinding had the highest. Significant difference in temperature between pure oil MQL and oil–water MQL was not found in grinding.

5.3 Machining with Vegetable Based Cutting Fluids

Although attempts in manufacturing research are focused to diminish the use of cutting fluids, the present state-of-the-art technologies do not seem to assure that cutting fluids will be entirely eliminated in the next future [67]. Some machining operations and workpiece materials have still required the use of cutting fluid. New trend concerning the cutting fluids in machining is to replace hazardous components with environmentally friendly compounds. These new compounds not only must show the same properties to cutting fluids but also must improve the machining performance such as productivity.

Literature studies about machining using vegetable based cutting fluids are limited. Higher cost of vegetable based oils relative to mineral based oils is the principal limitation of them but this drawback will be diminished in the future as the petroleum prices increase [68].

Literatures associated with vegetable based cutting fluids in drilling, turning, milling and grinding have presented in this section.

5.3.1 Drilling

Kelly and Cotterell [38] used vegetable oil as MQL lubricant during drilling of cast aluminium silicon alloys. The effect of various methods of cutting fluid application (flood lubrication, MQL-mist, compressed air and dry) on cutting temperatures, torque, cutting forces and surface roughness were investigated. MQL using vegetable oil gave lower feed forces, torques and surface roughness at the higher cutting speeds and feed rates. Flooding with mineral oil showed lowest cutting temperature. Costa et al. [43] studied the height of the burr under dry machining, MQL at the flow rate of 30 ml/h and conventional way (flooding) in the drilling. Vegetable oil in MQL, mineral oil in MQL and flooding and semi-synthetic oil in flooding were used as a cutting fluid. The smallest burr height was obtained for the dry drilling and the largest for the MQL systems. The MQL with vegetable oil generally produced smaller burr heights than that of the MQL with mineral oil. Rahim and Sasahara [69] studied MQL palm oil (MQLPO) as a lubricant in the high speed drilling of Ti-6Al-4V and for the comparison purpose MQL synthetic ester (MQLSE), air blow and flood conditions were used. MQLPO gave lower tool wear rate than MQLSE and flood condition also showed low flank and corner wear rate. For flood condition, both wear rates laid between MQLPO and MQLSE however the tool life was the same. MOLPO exhibited lower tool wear rate than MQLSE and air blow conditions and comparable with flood condition. Significant improvement of the friction and wear in palm oil was due to the fatty acid content of palm oil. The carbon chain length of the fatty acids in palm oil is longer than the synthetic ester and this increment enhances durability of the contact. Reaction between metal oxide layer and the fatty acid leads smooth sliding and low friction. Metal soap has been formed on the contact surface owing to this reaction. Longer carbon chain can resist high cutting temperature so protects the surface. The molecular thin film present during the drilling under MQLPO reduced the friction and heat generation thus improved tool wear. Besides, the high viscosity of palm oil has a tendency to resist the flow, providing effective lubricating at the tool-chip interface, which reduces the friction, thus prevent the cutting tool from rapid wear. They found that MQL and flood condition have similar effects on the tool wear rate and tool life. The lowest thrust force and torque were obtained with flood condition. MQLPO exhibited comparable performance to the flood condition with respect to maximum workpiece temperature. Belluco and De Chiffre [67] determined the efficiency of vegetable based cutting fluids in drilling of AISI 316L austenitic stainless steel by measurement of tool life, tool wear, cutting forces and chip formation. A commercial mineral based cutting fluid was taken as a reference fluid. It was found that all vegetable based cutting fluids performed better than the reference mineral based cutting fluid. The best performance was achieved with a vegetable based cutting fluid giving 177 % increment in tool life and 7 % reduction in thrust force. Kuram et al. [68] formulated crude and refined sunflower based cutting fluids and used these vegetable based cutting fluids during drilling so that evaluated the performance of them measuring the thrust force and surface roughness. Sunflower based cutting fluid prepared using two different surfactants showed smaller force and surface roughness values as compared to using only one surfactant. Refined sunflower based cutting fluid gave lower surface roughness than crude sunflower based cutting fluid, while crude sunflower based cutting fluid showed lower thrust force than refined sunflower based cutting fluid. Belluco and De Chiffre [70] investigated the performance of vegetable based cutting fluids with determining the cutting force and power in the drilling, core drilling, reaming and tapping of AISI 316L stainless steel. Vegetable based cutting fluids could achieve equal or better efficiency than the reference commercial mineral oil in all operations [70]. Kuram et al. [71] investigated the effect of cutting fluids developed from raw and refined sunflower oil and two other commercial (vegetable and mineral based) cutting fluids on thrust force and surface roughness during drilling of AISI 304 stainless steel. Refined sunflower cutting fluid showed better or comparable performance to commercial vegetable based cutting fluid depending on cutting conditions. Vegetable based cutting fluids developed from refined sunflower oil performed better than that of semi-synthetic and mineral cutting fluids during drilling of AISI 304 austenitic stainless steel [72].

5.3.2 Turning

Khan and Dhar [12] investigated the effect of MQL by vegetable oil on cutting temperature, tool wear, surface roughness and dimensional deviation in turning of AISI 1060 steel. MQL reduced the cutting temperature, tool wear and surface roughness as compared to dry machining. The reduction of about 5–12 % at average cutting temperature using MQL by vegetable oil as compared to using dry machining was observed depending upon the levels of the process parameters (cutting speed, feed rate). Cutting forces decreased by about 5–15 % using MQL by vegetable oil. Ozcelik et al. [31] reported the experimental studies of sunflower and canola oils based cutting fluids including different percentage (8 and 12 %) of extreme pressure additive and two commercial cutting fluids (semi-synthetic and mineral based) in turning of AISI 304L stainless steel with respect to surface roughness, cutting force, feed force and tool wear. Experiments were also conducted at dry cutting conditions which caused rapid tool wear and fracture. Tool life below 200, 1,000 and 2,000 s were recorded under dry cutting, semi-synthetic and mineral based cutting fluids, respectively. The higher tool life in vegetable based cutting fluids was due to the fatty acid content. Canola based cutting fluids showed better performance than sunflower based cutting fluids because of different length of carbon chains. Canola oil has three carbons more in formulae and longer carbon chain outstand high cutting temperature, thus improving the surface protection. Moreover, the high viscosity of canola oil had a tendency to resist flow. This high viscosity provides more effective lubricating at the tool-chip interface, thus reduces the friction between the tool and workpiece and removes heat developed at the interface easily. High percentage of extreme pressure additive in vegetable based cutting fluids showed the higher surface roughness values. 8 % of extreme pressure additive included canola based cutting fluid performed better than the rest [31]. Higher rate of EP in sunflower and canola based cutting fluids reduced cutting and feed forces during turning of AISI 304L austenitic stainless steel, however the increment of EP rate affected surface roughness values negatively. As a result, mineral and semi-synthetic cutting fluids can be replaced by vegetable based cutting fluids in turning [16]. Ojolo et al. [73] used vegetable based cutting fluids (groundnut oil, coconut oil, palm kernel oil and shear butter oil) during turning of mild steel, aluminum and copper and measured cutting force. Although, it was found that the effects of vegetable based cutting fluids were material dependent, groundnut oil showed the best performance among the four vegetable based cutting fluids investigated. Xavior and Adithan [74] used coconut oil during turning of AISI 304 stainless steel and measured tool wear and surface roughness. The performance of coconut oil was compared with an emulsion and a neat cutting oil. They found that coconut oil reduced the tool wear and improved the surface finish. In another study they measured temperature and cutting force [75]. Coconut oil outperformed the other two cutting fluids (soluble oil and straight cutting oil) in terms of reducing the cutting force and temperature. Paul and Pal [76] investigated the performance of different types of cutting fluids (karanja oil, neem oil, conventional fluid) as compared to dry cutting condition during turning of mild steel. The use of vegetable based cutting fluid improved surface quality as compared to dry turning and conventional cutting fluid. They explained the lower temperature of neem vegetable oil than that of karanja vegetable oil with the lower viscosity of neem oil with respect to karanja oil.

5.3.3 Milling

Sales et al. [56] evaluated tool wear, surface roughness and burr formation when milling AISI 4140 steel with vegetable based cutting fluid applied by MQL technique using different flow rate (dry cutting, 50, 100, 150 and 200 ml/h). They stated that the vegetable cutting fluid efficiently accessed and remained at the chip-tool interface longer. This fact was due to the capability of vegetable oil' creating a thin film of molecular layer. This thin film improved boundary lubrication, thus decreased friction at the cutting interface. Increment in coolant flow rate tended to reduce tool wear, surface roughness and burr length. In milling of 15-5 precipitation-hardened martensitic stainless steel, Junior et al. [77] used four different cooling and lubrication conditions: flood of vegetable oil-based emulsion, low flow of neat vegetable oil, application of neat vegetable oil in a flow of compressed air (MQL) and dry cutting. The longest tool life was obtained with low flow of neat vegetable oil, followed by neat vegetable oil under MQL. Flood of vegetable oil-based emulsion showed worst performance. Kuram et al. [78] developed vegetable based cutting fluids from refined canola and sunflower oil which were used in milling of AISI 304 stainless steel and their tool wear and cutting force performances were compared to a commercial type semi-synthetic cutting fluid. Canola and sunflower based cutting fluids gave better performance than semi-synthetic cutting fluid.

5.3.4 Grinding

Oliveira and Alves [79] formulated new water based cutting fluid (sulfonate vegetable oil in water) able to meet both the grinding performance and environmental requirements. As a vegetable oil they selected sulfonate castor oil obtained from a plant called *mamona* in South America. The authors selected this oil owing to its abundance in South America and its stability. The new cutting fluid did not contain any banned products in its formula such as chlorine substances and nitrosamines. From the biodegradability test results it was concluded that the new cutting fluid was easily biodegradable, was not detrimental to the environment and its disposal could be easily made. The grinding experiments were conducted at SAE 8640 workpiece material. Cutting oil and semi-synthetic cutting fluid were selected as reference fluids so that the performance of the new cutting fluid is compared. In the grinding experiments, several dilutions (35, 45 and 70 % in volume) of this new cutting fluid were tested. The lowest and highest grinding ratios (G ratio-material removed volume/wheel worn volume) were measured using semi-synthetic cutting fluid and neat oil, respectively. The new cutting fluid concentrated at 45 % gave the closest performance to oil, i.e. high G ratio. The lowest surface roughness values were achieved with the new cutting fluid at the concentration of 45 % and the lowest force values were obtained when using new fluid at 45 % and the neat oil. As a result, new cutting fluid gave comparable performance to the obtained with neat oil. In an another study, they used new castor cutting fluid at 15, 21 and 32 % concentrations [80]. The lowest wheel wear (high G ratio) and the highest wheel wear were observed with cutting oil and semi-synthetic cutting fluid, respectively. The concentration of 21 % gave similar performance to the cutting oil. The lowest surface roughness was obtained at 21 % concentration. Alves and de Oliveira [17] used castor oil in grinding and found that new vegetable based cutting fluid was readily biodegradable. Wheel wear, grinding forces and surface roughness reduced when the new cutting fluid diluted at 45 % was used.

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