Chapter 2
Use of Vegetable-Based Cutting Fluids for Sustainable Machining

R.R. Srikant and P.N. Rao

Abstract Cutting fluids are popularly used in machining to reduce cutting forces, temperatures and thus prolong the tool life. However, cutting fluids are complex compounds containing different ingredients some of which are toxic. Constant exposure to these fluids causes severe health hazards to the workers. Further, the disposal of the cutting fluids adds to the cost due to the required chemical treatment. Hence, the concept of using minimum quantity lubrication (MQL) has come into picture. Further, to make the fluids more benign, vegetable-based compounds are being used to replace the toxic ingredients. This is done in different levels, i.e., either only the mineral oil in the fluid is replaced by vegetable oil or even the emulsifier is replaced by a vegetable alternative. The present chapter discusses MQL and vegetable-based cutting fluids for sustainable machining. Results obtained during the application of vegetable oils are presented.

2.1 Introduction

Material removal is one of the most important processes in the manufacturing industries because of its ability to provide the required surface finish and dimensional tolerance. This process involves the removal of material from the workpiece using a hard cutting tool by plastic deformation. All the energy consumed for plastic deformation during the transformation of the workpiece to chips is converted into heat. A majority of the heat is generated in the shear plane because of internal friction, and this accounts for a large amount of heat generated of the order of 65–75%. Next, the friction at the chip–tool interface causes a heat of the order of 15–25% to be generated, while the friction at the tool work interface generates a heat of the order of 10% (Fig. 2.1). The generated heat moves into the cutting tool, workpiece, and the surrounding atmosphere by way of conduction, convection, or radiation depending upon the ambient conditions. The amount of heat generated

R.R. Srikant (✉) · P.N. Rao
Department of Technology, University of Northern Iowa, Cedar Falls, IA, USA
e-mail: rukmini.revuru@uni.edu

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depends upon the hardness of the workpiece material as well as the amount of material removed and the removal rate. A major portion of the generated heat is carried away by the chips, while the remaining heat is dissipated into the workpiece and cutting tool [1]. This leads to accelerated tool failure and thermally damage the workpiece. The thermal damage to the workpiece ranges from bad surface finish to induced residual stresses, microcracks, and corrosion (Sukaylo et al. 2005). Further, the elevated cutting zone temperature significantly promotes the formation of built-up edge (BUE) on the tool tip. BUE leads to inconsistent cutting forces and poor surface finish of the product [2].

To alleviate these problems, metalworking fluids (also called as cutting fluids) are extensively used during industrial machining operations [3]. In addition to cooling action, cutting fluids also lubricate the machining zone leading to reduced cutting forces. Application of cutting fluids also helps in achieving longer tool life and better quality of the product [4]. In the present market, many varieties of cutting fluids are available. Nevertheless, water miscible oils are used for over 70% of the applications [1]. Water miscible oils contain both oil and water in them, thus combining the lubricating and cooling abilities. SPS (Sodium petroleum sulfonate), a petroleum-based emulsifier, is used to hold the water and oil molecules together [5]. Traditionally, these cutting fluids were applied in the form of flooding of fluid in large quantities at the backside of the chip to extract a major amount of the heat generated during the machining process [6]. The fluids are recirculated in the system and are compensated for any losses due to evaporation. Continuous reuse of the fluids deteriorates their performance. Further, the effects of the fluids on workers' health, handling, and disposal issues, environmental pollution, etc. are major concerns for the industries [7]. Huge money is spent each year to chemically treat and dispose the used cutting fluids. As a result of regular usage, the fluids lose their functionality to the point where these fluids need replacement. The ingredients in cutting fluids such as the EP additives and emulsifier make the cutting fluid non-biodegradable. This often calls for special treatment before disposal and increases the disposal costs.

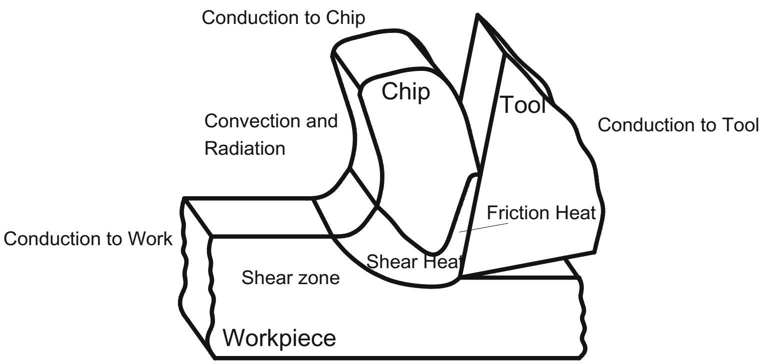

Fig. 2.1 Generation and distribution of heat during machining

Almost 80% of the occupational diseases are caused due to the microbial contamination and toxic composition of the fluids [7]. The chemical reactions amid the formulation cause even simple compounds to be toxic. It is reported by International Agency for Research on Cancer (IARC) that cutting fluids containing petroleum-based additives cause skin cancer [8]. Many other diseases such as lung cancer, respiratory disorders, and various dermatological diseases may be caused due to the regular use of cutting fluids [9]. In USA, it is reported that in 1999, more than 100 million gallons of metalworking fluids were used and a total of 1.2 million employees were exposed to the harmful effects of these cutting fluids and are likely to face potential health hazards. As per the US National Institute for Occupational Safety and Health (NIOSH), the permissible exposure level for metalworking fluid (MWF) aerosol concentration is 0.5 mg/m^3, while the oil mist level in the US automotive parts manufacturing facilities has been estimated to be 20–90 mg/m^3 with the use of conventional lubrication by flood coolant.

The bacterial genus found in the cutting fluids is alarming. Aerobic bacteria grow exponentially in the cutting fluids in both stored and working conditions. The bacterial genus is identified as Pseudomonas. This being an opportunistic bacterium aggravates in case of an injury or burns, which are common in a machining shop. There are about seventy species in Pseudomonas, majority of which have the ability to break down the oils (which can crucially affect the cutting fluid). The organisms feed on the carbon present in the oils and deteriorate the oil into an inorganic compound. Pseudomonas has the ability to survive in hostile conditions and is not suppressed even by biocides [10]. Also, the use of biocides in the cutting fluids is restricted by several constraints imposed by the environmental regulations of various organizations [11].

Addition of different additives like chlorinated paraffin to increase chemical stability, viscosity, flame resistance, etc. further aggravate the problem of disposal [12]. These additives change to dioxin on heating and can lead to uncontrolled burning. Hence such cutting fluids are classified as hazardous compounds [13].

To deal with the problems associated with conventional cutting fluids, newer blends of cutting fluids came into existence.

In order to achieve sustainable machining, it is necessary to reduce the use of the amount of cutting fluid used, while simultaneously replacing it with 100% biodegradable oil. The negative consequences of the flooding application of cutting fluids have prompted the researchers to look for alternative solutions to the use of flooding. Few of the alternatives that were considered are as follows:

- Dry machining,
- Compressed gas cooling,
- Internal cooling,
- Coatings on cutting tools,
- Cryogenic cooling, and
- Minimum quantity lubrication (MQL).

Of all these methods, MQL has been found to be reasonably good for a number of machining situations [14].

2.2 Minimum Quantity Lubrication (MQL)

The application of low quantities of cutting fluids is currently termed as minimum quantity lubrication (MQL). The concept of MQL arises from the fact that a majority of the cutting fluid used in flooding is not really utilized for any purpose other than flushing chips and splashing. The idea of MQL is not new, and a lot of interest was demonstrated in 1960s and 1970s when it was called as mist cooling. The main purpose here is to use as little cutting fluid as required that provides just enough cooling and lubrication for the required situation. General range of flow rate in MQL is of the order of 5–500 mL/h. This is far less than the conventional quantities, which are of the order of 120,000 mL/h. This low volume of fluid can be supplied with or without the assistance of compressed air. A pump supplies the cutting fluid dropwise without any compressed air, which would not be efficient for flushing chips from the machining zone. The more common usage is the fluid mixed with compressed air, which atomizes the fluid into very small droplets, and the pressurized jet is focused on the machining zone. MQL application of cutting fluids gives superior performance over flooding because of the following reasons:

- The small size of the particles in mist improves the penetrating ability of the cutting fluids.
- Large surface to volume ratio for each drop provides the possibility of rapid vaporization, which is an important step that must precede penetration of the chip–tool interface.

Since the amount of cutting fluid in MQL is very small, the cooling effect will be relatively small while lubrication plays a major role and hence the name MQL. The minimum quantity lubrication method involves the application of atomized cutting fluid with the help of compressed air at a typical pressure of 4–6 bar through a specially designed nozzle directed at a position close to the cutting zone. The nozzle diameter is about 1–2 mm. In MQL, as the cutting fluid droplets meet the heated cutting zone, they evaporate, extracting the latent heat from the machining zone. Since the convective heat transfer is small compared to evaporative transfer, substantial amount of heat will be removed in MQL. Since all the cutting fluid is evaporated during contact with the workpiece and tool surfaces, there is no waste-disposal problem, making clean chips compared to conventional flood cooling. The vaporized cutting fluid then easily penetrates the chip–tool interface and provided the required lubrication to reduce the friction between the chip and the cutting tool rake face. In view of this, the MQL nozzle should ideally be positioned close to the flank face, so that the oil mist will go through the tool tip and then go past the tool rake face. Positioning it at the back of the chip should be avoided as it will not be able to penetrate the rake face to provide lubrication ability. Due to the limitations and hazards associated with flood lubrication, MQL is gaining prominence [15]. Minimum quantity lubrication technique offers several advantages over conventional flooding as below:

- MQL utilizes comparatively very little amount of cutting fluid making it almost dry and clean.
- The aerosol of the cutting fluid vaporizes quickly removing the heat while making the process clean and environmentally friendly. The emissions from MQL are low and healthier for the workers compared to flooding.
- The use of compressed air flushes away the chips more efficiently, thus making chip disposal a much easier task.
- Experimental evidence presented so far indicates that minimum quantity lubrication will be more productive, with an increased tool life and better surface finish.

Attanasio et al. [16] studied the machining of 100Cr6 steel with the application of cutting fluid in different supply directions, namely on the rake face and flank face. It was reported that application of the cutting fluid on flank face is most effective strategy to reduce tool wear. Lesser tool wear was observed while using MQL compared to dry machining. da Silva et al. [17] studied the efficacy of MQL in grinding. Surface roughness, residual stresses, microhardness, and microstructure were used to evaluate the performance. It was found that MQL can be effectively used in grinding, and the process was environmentally benign. Surface roughness reduced substantially with the use of MQL. Though microstructure was not much effected, residual compressive stresses increased with use of MQL, which is favorable. Sadeghi et al. [18] machined Ti–6Al–4V under different cutting conditions in the application of MQL and flood lubrication. While soluble oil (5% concentration) was used in flood lubrication, synthetic fluids and vegetable oils were used in MQL. It was reported that MQL reduced the tangential force compared to flooding. Interestingly, higher surface roughness was observed with MQL. The flow rate of MQL was found to be a significant parameter affecting the performance of MQL. Under the considered parameters, synthetic fluids performed better than the vegetable oils. Tawakoli et al. [19] studied the influence of flow rate, flow pressure, MQL nozzle position, and distance on grinding performance. Cutting forces and surface roughness were observed. It was reported that by proper control of nozzle and flow parameters, MQL drastically reduced the cutting forces and surface roughness. It was found that when spray nozzle is positioned angularly toward the wheel (at approximately 10–20° to the workpiece surface), optimum performance was observed. In their studies, a flow rate of 90 mL/h, 6 psi air pressure, and 70–90 mm nozzle distance from the grinding wheel were found to guarantee adequate wetting of the grinding wheel.

While many studies concentrated on application of neat oils/synthetic fluids in their concentrated form in MQL, studies using water soluble oil in MQL are not rare. Hadad and Sadeghi [20] studied the machining of AISI 4140 steel under dry, flood lubrication, and MQL environments. Different cutting conditions and application directions of MQL were studied. It was found that MQL consistently outperformed the other two methods due to the reduction of cutting forces through proper lubrication. This helped in generating lesser temperatures and hence lesser tool wear and surface roughness.

From the available literature, it can be noted that in the recent years, MQL has received increased attention. Different cutting fluids have been tested in MQL. Due to the smaller size of the droplet, the cutting fluid has better chances to reach the tool–workpiece contact zone in MQL than in flood lubrication. MQL has consistently shown better performance compared to dry machining and flood lubrication. However, the efficacy of MQL depends on the properties of the cutting fluid. Hence, different formulations of cutting fluids with enhanced properties were tested. In this scenario, the use of nanofluids as cutting fluids in machining has gained momentum. Different nanoparticles such as graphite, Al_2O_3, MoS_2, MWCNTs, graphite [21], CNT [22], MoS_2 [23], and boric acid [24] have been used to develop nanocutting fluids. The base fluids ranged from pure vegetable oils to water miscible cutting fluids. It is reported in literature that nanocutting fluids help to decrease tool wear, surface roughness, cutting forces, and cutting temperatures as compared to MQL with regular cutting fluids. However, perhaps owing to the high cost of nanoparticles, the reported works deal only with constant cutting conditions. In order to assess the performance of a cutting fluid in machining, it is necessary to understand its behavior at different conditions. Though the addition of nanoparticles is advantageous in terms of performance, the cost and handling issues are alarming.

2.3 Vegetable-Based Cutting Fluids

The cutting fluids that are well suited for MQL are with very good lubricity and high flashpoint to reduce the mist formation. MQL drastically reduces the impact of the cutting fluids on the ecology. This can be further improved if a completely biodegradable cutting fluid is used. However, the machinist is constantly exposed to the fluids. Owing to the low flash point (about 215 °C), the mineral-based oils tend to generate mist which is often inhaled by the workers. On the other hand, vegetable oils have a higher flash point, and hence do not pose this problem. Further, vegetable oils have a distinct advantage of being renewable, clean, and abundant. Vegetable oils are highly biodegradable due to easy hydrolization of glycerin ester groups. The unsaturated double bond is susceptible to decay very easily [25], and as a result, they do not have good shelf life. Vegetable oils provide better lubrication compared to mineral oils and form anti-friction adsorption films on metallic surfaces [26]. Thus, vegetable oils provide better lubrication and are environmental friendly. Some of the properties of common vegetable oils that are relevant to their use as cutting fluids is given in Table 2.1. In light of the above reasons and to reduce the occupational health hazards posed by the cutting fluids, the mineral-based oil in the cutting fluids (both neat oils and water miscible oils) is being replaced by vegetable alternatives. With the increase in demand for biodegradable cutting fluids, the market for such formulations has expanded [27].

Table 2.1 Properties of some of the vegetable oils [7]

Properties	Soybean	Sunflower	Rapeseed	Jatropha	Neem	Castor
Kinematic viscosity @ 40 °C (cSt)	32.93	40.05	45.6	47.48	68.03	220.6
Kinematic viscosity @ 100 °C (cSt)	8.08	8.65	10.07	8.04	10.14	19.72
Viscosity index	219	206	216	208	135	220
Pour point (0 °C)	−9	−12	−12	0	9	−27
Flash point (0 °C)	240	252	240	240	–	250

Several blends of such cutting fluids are available in the market. Initially, the share of such lubricants was about 2% in the worldwide lubricant market, and now, the growth is anticipated at a rate of 7–10% annually in US [25].

Vegetable oils are used in two different approaches, as neat oils and as an ingredient in the water miscible cutting fluid. Avila and Abrao [28] machined AISI 4340 steel under the application of a vegetable oil, a mineral oil-based fluid and a synthetic fluid. It was observed that vegetable oil-based fluid gave longer tool life and improved the surface finish. Belluco and De Chiffre [29, 30] studied the performance of cutting fluids formulated using rapeseed oil, ester oil and sulfur, and phosphor additives in drilling AISI 316L austenitic stainless steel. The results indicated that the vegetable-based fluids were better than the mineral fluids as they resulted in longer tool life, better chip breaking, and lesser cutting forces. About 117% increase in tool life was reported.

Khan and Dhar [31] machined AISI 1060 steel under MQL with a vegetable oil. Cutting temperatures, tool wear, and surface roughness were studied. Cutting temperatures were found to reduce by about 5–12% and cutting forces by 5–15% compared to dry machining. Sharif et al. [32] used a cutting fluid with palm oil and compared the performance with dry machining and flood lubrication. Tool wear progression was found to be slower for palm oil-based cutting fluid. Tool life of 160.27 min was observed for palm oil-based cutting fluid, while it was 39.86 min for flood lubrication and 35.16 min for dry cutting. Similar results were obtained by Xavior and Adithan [33] who used coconut oil in MQL.

Kuram et al. [34] machined AISI 304 steel under MQL using sunflower oil-based cutting fluid, sunflower-based cutting fluid with surfactants, commercial vegetable oil, and mineral oil-based fluid. It was observed that sunflower-based fluid produced parts with best surface finish. Paul and Pal [35] compared the performance of vegetable-based cutting fluids (karanja and neem oil) and conventional cutting fluid with mineral oils. It was observed that neem oil produced lesser cutting temperatures compared to karanja oil and regular conventional fluid.

Ozcelik et al. [9] tested cutting fluids with sunflower oil, canola oil, and mineral oils. It is reported canola oil showed better performance compared to sunflower oil-based cutting fluids due to the variation in the lengths of carbon chains. Also, the higher carbon content and higher viscosity of canola oil helps in better lubrication. It was also noted that addition of EP additives may reduce the cutting forces but do not have a positive effect on the surface finish. Talib and Rahim [36] modified the chemical structure of jatropha oil (MJO) by transesterification process with different molar ratios of jatropha methyl ester (JME). The modified oils were tested for basic properties such as viscosity, density, and lubricity. These fluids were used in MQL, and the performance was compared with synthetic fluids. It was found the modified oils were good in reducing the cutting forces and temperatures.

Kumar et al. [37] studied sesame and coconut oil with EP additives in machining AISI 1040 steel. Coconut oil reduced the feed force by 31%, thrust force by 28%, cutting force by 20%, cutting tool temperature by 7%, and tool flank wear by 34% compared to other considered fluids.

Zhang et al. [38, 39] and Rao et al. [40] have utilized soy-based cutting fluid in their experimentation to evaluate the utility of this compared to other petroleum-based cutting fluids that are traditionally utilized. The advantages with the soy-based cutting fluids are as follows:

- Biodegradable and renewable, since it is coming from an agricultural product.
- No harmful additives are added unlike the petroleum products that use the EP additives such as chlorine and Sulfur.
- Because of the higher flash point, the amount of mist generated is very small which will help reduce the environmental pollution as well as providing a better machine shop atmosphere. This should reduce the medical problems to the operators that are working with the machines.
- Though the initial cost of soy fluids is more, the overall cost of usage should reduce because of the higher lubricity of these fluids.

They conducted experiments in turning AISI 4140 steel and 52100 steel using carbide tools on a Haas SL-20 turning center. They measured surface roughness and tool wear during the experimentation. The cutting fluid is applied in the form of flooding as is universally used by manufacturing industries. The machining parameters chosen were close to the industrial practice.

Experimental data collected was analyzed using ANOVA and student *t*-test to compare the performances of the soybean-based cutting fluid in comparison with the petroleum-based fluid and dry cutting. The ANOVA test and *t*-test for the effect of cutting fluids on surface roughness for AISI 4140 is shown in Tables 2.2 and 2.3, respectively. The student t-test result for surface roughness can be also visualized through one-way analysis figure that is displayed in Fig. 2.2. The ANOVA test and *t*-test for the effect of cutting fluids on tool wear for AISI 4140 are shown in Tables 2.4 and 2.5, respectively. The student *t*-test result for surface roughness can be also visualized through one-way analysis figure that is displayed in Fig. 2.3.

Table 2.2 Analysis of surface roughness for AISI 4140

Source	DF	Sum of squares	Mean square	F ratio	Prob > *F*
Fluids	2	36.61469	18.3073	4.3964	0.0203
Error	33	137.41690	4.1641		
C. Total	35	174.03159			

Table 2.3 Average comparison for each pair of treatments using student's t

Level			Mean
1	A		5.5733333
2		B	3.5083333
3		B	3.3666667

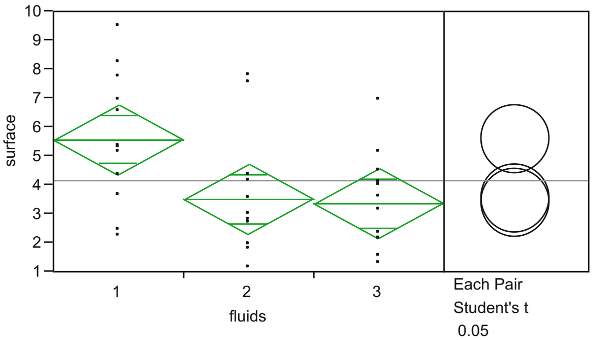

Fig. 2.2 One-way analysis of surface with cutting fluids for AISI 4140

Table 2.4 Analysis of variance of tool wear for AISI 4140

Source	DF	Sum of squares	Mean square	F ratio	Prob > *F*
Fluids	2	0.08178117	0.040891	12.3798	<0.0001
Error	33	0.10899958	0.003303		
C. Total	35	0.19078075			

Table 2.5 Average comparison for each pair of treatments using student's t

Level				Mean
1	A			0.30741667
2		B		0.25450000
3			C	0.19083333

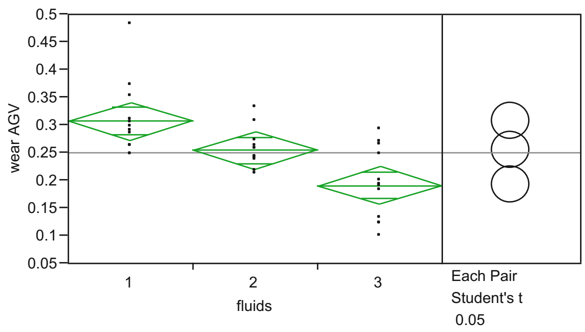

Fig. 2.3 One-way analysis of average tool wear with cutting fluids for AISI 4140

The result of the data analysis can be summarized as:

- The soybean-based cutting fluid provided surface finish similar to that of the petroleum-based fluid with AISI 4140 and 52100 steels,
- The soybean-based cutting fluid also reduced tool wear compared to dry cutting condition for both steels, and
- The soybean-based cutting fluid did not perform as good as the petroleum-based cutting fluid in reducing tool wear for both steels.

The inclusion of microadditives/nanoadditives in vegetable oils is also found in literature. Padmini et al. [24] studied the influence of nanoMoS_2 in coconut, sesame, and canola oils for MQL in turning of AISI 1040 steels. It was observed that inclusion of nanoparticles in coconut oil gave better performance compared to all other conditions.

Some of the studies on application of vegetable oil-based MQL are presented in Table 2.6.

In a strikingly different approach, Srikant and Ramana [42] have replaced both the oil and emulsifier in the cutting fluid with vegetable derivatives. Sesame oil and Cocamidopropylbetaine (CAPB) were used as the oil and emulsifier, respectively. CAPB is an emulsifier with high water solubility. It is highly biodegradable and can work with any liquid. CAPB is obtained from coconut oil. The cutting fluids were formulating different levels of oil and CAPB. The formed mixtures were diluted with water in the ratio of 1:19.

The formulated fluids were applied in the form of flooding during turning and cutting forces, temperatures, tool wear, and surface roughness were measured. It was observed that increased levels of CAPB gave better performance in all the cases, but not much improvement was observed beyond 10% (Fig. 2.4). The basic properties of the fluids were evaluated to draw an inference on the behavior of the fluids [43]. The fluids were also tested for their corrosive nature and quenching effects to assess the applicability of the fluids while machining different materials

Table 2.6 Experimental results for vegetable oil-based MQL

Machining process	Material	Cutting fluid	MQL parameters	Reference	Cutting process improvement
Drilling	Al alloy ACP 5080, BHN 85	Vegetable oil	20 mL/h, 6 bar pressure	[29]	Surface finish improved
	Titanium, Ti6Al4V	Synthetic ester, palm oil	10.3 mL/h, 165 L/min air flow at 0.2 MPa	[44]	MQL comparable to flooding with Palm oil. Synthetic ester is inferior to palm oil
	AISI 316 stainless steel	Coconut oil, palm oil, olive oil, and sesame oil	10 mL/h	[30]	Coconut oil gave the smoothest surface and the best performance at cutting speed = 12.192 m/min, depth of cut = 23 mm, feed rate = 54.8 mm/rev, and spindle speed = 456 rpm
Turning	AISI 9310 steel	MQL—food-grade vegetable oil, Flood-Ecocut San 220	100 mL/h	[45]	MQL resulted in improved tool life, surface finish, and chip characteristics at all considered cutting conditions
	AISI 52100 steel	Coconut oil, Servocut S	1 L/h	[46]	Coconut oil produced lesser surface roughness
	AISI 1040	NanoMoS_2 + coconut oil, sesame oil, and canola oil	10 mL/min	[24]	Coconut oil—cutting forces reduced by 37%, temperatures by 21%, tool wear by 44% compared to dry machining
Milling	Inconel 718	Biodegradable vegetable oil, Bescut 173	8 mL/h	[47]	Tool life increased by 1.57 times in MQL compared to dry machining
	AISI 1040	Vegetable esters	11.5 mL/h	[20]	Reduced tool wear, forces in MQL compared to dry machining
Grinding	Ti–6Al–4V	Castor oil + Al_2O_3	18 mL/h	[48]	Grinding forces and surface roughness reduced with MQL
	GH4169 Ni-based alloy	Synthetic lipids + MoS_2 and CNT	50 mL/h	[26]	Nanofluid MQL gives better precision and surface quality due to lubrication. Performance related to concentration levels

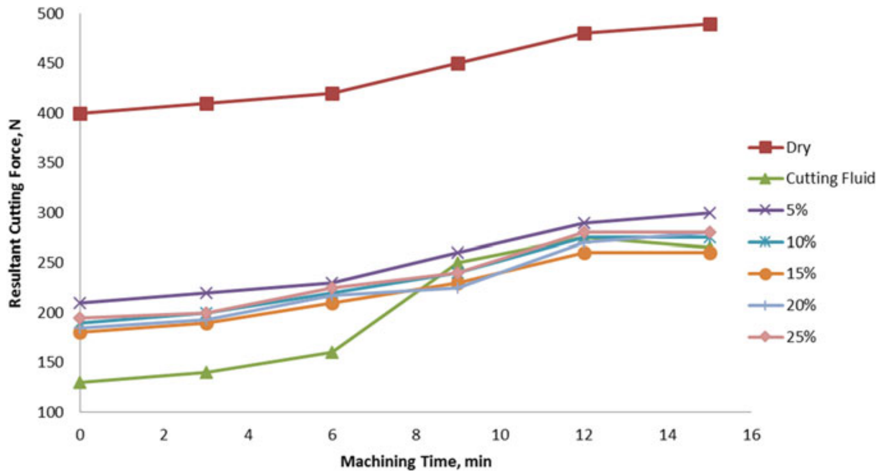

Fig. 2.4 Variation of cutting forces with machining time when using different cutting fluids

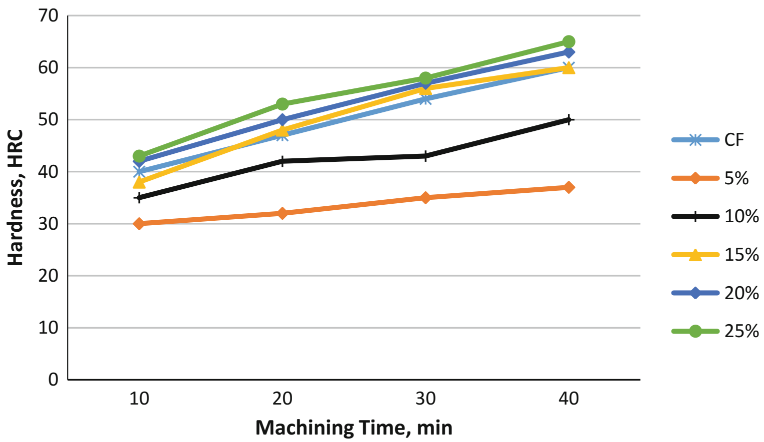

Fig. 2.5 Hardness of machined samples

[43]. It was found that while 20% CAPB fluid gave the highest hardness (Fig. 2.5) to the samples due to the thermal conductivity, 15% CAPB fluid showed lesser corrosive tendency (Fig. 2.6).

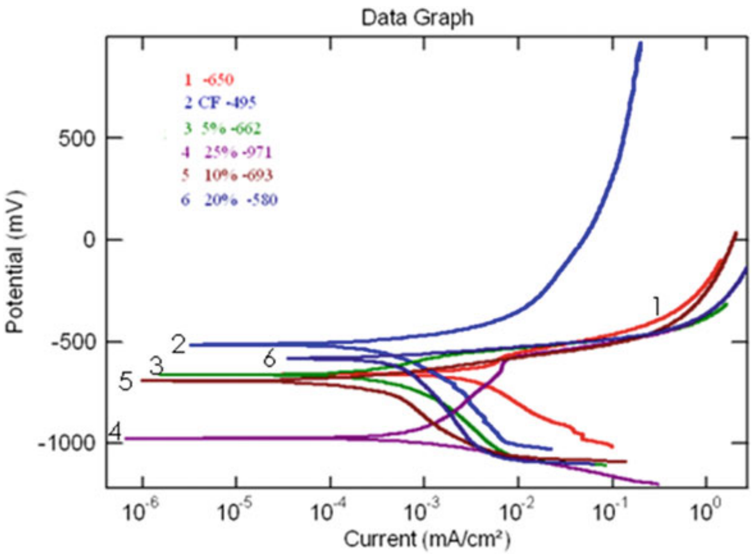

Fig. 2.6 Corrosion results

2.4 Summary

Traditionally cutting fluids are used to carry away the heat and reduce the friction produced in machining. In a majority of the applications, water miscible cutting fluids are used. Conventional cutting fluids suffer from many limitations such as environmental and disposal issues. Hence, the concept of MQL is becoming significant. Small quantities of the fluid are supplied to the cutting zone in order to cool and lubricate the working zone. The fluid may be supplied in the form of a neat oil or as a water miscible cutting fluid.

As a further step towards sustainable manufacturing, the ingredients in the cutting fluids are being replaced with vegetable alternatives. Because of their superior properties, vegetable-based cutting fluids exhibit better performance compared to the mineral oils. Inclusion of nanoparticles in both mineral and vegetable oils to enhance the performance is tried by many researchers. But the cost of the particles is many times prohibitive. Future research may be directed at improving the performance of the fluids through alternate measures.

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