Role of Eco-friendly Cutting Fluids and Cooling Techniques in Machining

Kishor Kumar Gajrani and Mamilla Ravi Sankar

Abstract Nowadays with growing pollution and contamination by hydrocarbon (petroleum) based cutting fluids, the scope for vegetable or synthetic biodegradable esters based eco-friendly cutting fluids is increasing. In this review work, the main focus is on sustainable machining using advanced cutting fluid application techniques with eco-friendly cutting fluids. Understanding the functions and various types of cutting fluids are critically important to maximize its performance during any machining process. Also, cutting fluid application techniques are equally important to minimize the use of cutting fluids for the desired machining processes. This review article focuses on the conventional cutting fluids, function of cutting fluids, ecological aspects of conventional cutting fluids, eco-friendly cutting fluids, cutting fluid application techniques during machining and their performances in order to establish the research field further. An overview of the role of eco-friendly cutting fluids and cooling techniques are discussed and finally concluding remarks and possible scope of future work is presented.

Keywords Cutting fluids · Cryogenic cooling · Dry machining · Eco-friendly cutting fluids · Flood cooling · Minimum quantity lubrication (MQL) · Mist cooling · Sustainable machining

1 Introduction

In today's manufacturing world, machining is the most important field due to good quality product and high productivity. For achieving high productivity, machining parameters (depth of cut, feed and cutting speed) are significantly higher that leads

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to a large amount of heat generation, which results in higher machining temperature. Subsequently, surface integrity, tool life and dimension accuracy of the product deteriorated. Product with better surface integrity has the capability to improve its corrosion resistance, fatigue strength and its tribological properties. Therefore, better surface quality of the product is highly desirable as well as it is also an indicator of quality of machining [1, 2]. To reduce the machining temperature as well as to improve the product surface integrity and tool life, cutting fluids are necessary during machining operations.

From the last two century, cutting fluids are widely used in machining operations. Each year, the United States alone uses around 100 million gallons of metalworking fluids [3]. In the past, generally, water was used as cutting fluids on grindstones. Then, animal product based tallow was used as wax for the lubricating purpose. Afterwards, simple oils were applied to the cutting tool surface for better lubrication. At early 20th century, soap was added in water to reduce shear strength of mating surfaces [4]. In 1936, straight oils (mineral oils) were introduced as cutting fluids for metal cutting purposes. In 1944, chemicals were added in straight oils as additives for enhancing lubricating properties of cutting fluids [5]. The complexity of cutting fluid composition is increasing day by day with the introduction of hard metals for better performance in the world. From last two to three decades, chemical additives, emulsifiers, pressure additives, biocides, rust inhibitors are added in cutting fluids to fulfil the demands of industries [6]. Figure 1 illustrated the chronological development of metalworking fluids according to [7–10].

During machining, estimated 38 metric ton lubricants were used in the year 2005. Out of all, mineral-oil based cutting fluids comprise around 85% of the global demand [12]. Mineral oil based cutting fluids are made up of petroleum-based products (hydrocarbons), which also contains various additives such as phosphorus compounds, sulfurized oils, free sulphur and fatty acids. During machining, workpiece and tool material tend to react with these additives due to high temperature at cutting zone and hamper the surface integrity as well as workpiece properties. Also, it is well known that sulphides and phosphates are hazardous to the environment as well as operators health [13]. Moreover, due to prolonged exposure of these cutting fluids, operators may have to suffer from various respiratory and skin diseases [14]. Also, the growing cost and complexity of the disposal of cutting fluids are very complex [15]. Finally, it has been realised by researchers as well as industrialist that conventional mineral oil based cutting fluids have serious health effects on operators as well as have detrimental impact on the environment [16]. Even government and environmental protection agencies made strict norms and legalised it for public welfare [17]. Also, mineral oil based cutting fluids are limited. Therefore, a sustainable solution was needed to reduce the detrimental effect on the environment and health hazards to operators.

Cutting fluids need to be highly biodegradable as well as renewable apart from being better at machining to protect the environment. Nowadays, environmental aspects of cutting fluids are measured in terms of renewability, toxicity, biodegradability, biomagnifications and bioaccountability [18, 19]. Therefore, demand for new bio-based eco-friendly cutting fluids is increasing. In general eco-friendly cutting flu-

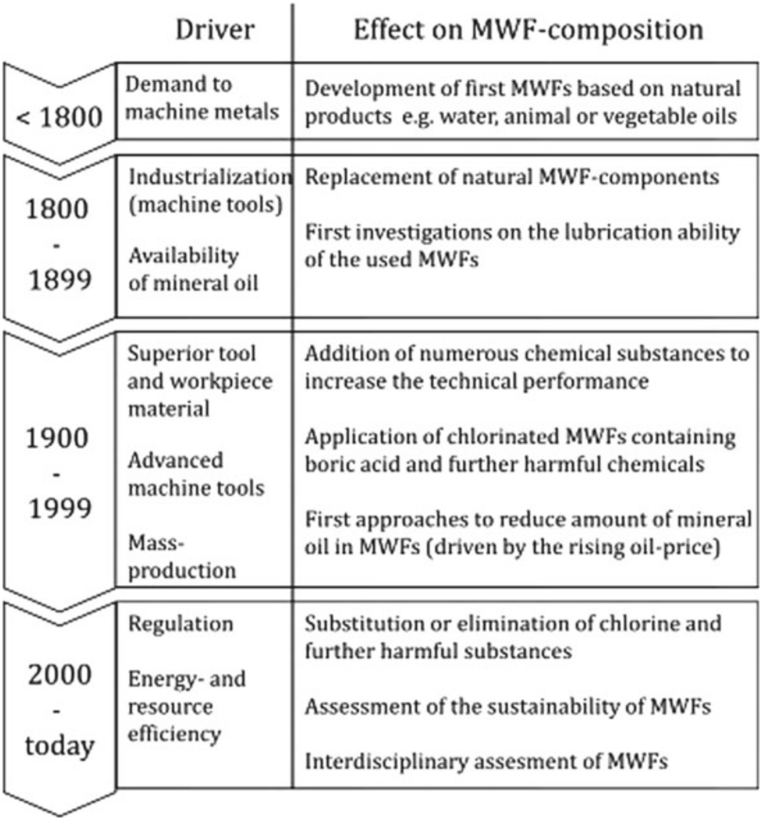


Fig. 1 Chronological development of metalworking fluids [11], with kind permission from Elsevier

ids are made up of vegetable-based oils, which are highly renewable, biodegradable, less hazardous and can be disposed of easily [20–22]. Concurrently, industries are also focusing on making machining cleaner by reducing or eliminating the amount of cutting fluids used for machining [23]. Near-dry machining (NDM) and dry machining are already known as eco-friendly machining technique and are also has been applied successfully for various machining operations [24–27]. Though, in few processes like hard turning and grinding, the use of cutting fluid is still necessary to reduce high temperature and to obtain better surface finish of workpiece [28, 29].

This study aims to find alternate answers and use protective measures against the detrimental environmental effects of conventional mineral oil based cutting fluids. Therefore, a review study is carried out to investigate the role of eco-friendly cutting fluids and cooling techniques in machining performance to find protective measures for sustainable production and a cleaner environment. This review work sums up the capability of eco-friendly cutting fluids and various cooling techniques in details.

2 Cutting Fluids

Traditionally, the cutting fluids are used to lubricate the chip-tool interface as well as the workpiece-tool interface. Also, cutting fluids other functions is to cool cutting zone and to flush away the chips from cutting area [30, 31]. Figure 2 illustrates the region of heat generation in machining.

2.1 Functions of Cutting Fluids

Cutting fluids are used in machining from more than last two centuries [20]. Cutting fluids have all four functions as mentioned above. However, its primary function is to reduce the cutting zone temperature and sliding friction [32, 33]. Nowadays, commercially available cutting fluids have wide varieties. As per the requirement of machining operations and the final output surface integrity, cutting fluids can be tuned towards more cooling or more lubrication. Cutting fluids effectiveness depends upon so many factors like its application technique, machining input parameters and type of machining operation [12].

In machining, cutting fluid lubrication property means to apply grease (in any form) to reduce abrasion and adhesion between the chip-tool interface and workpiece-tool interface [34]. Generally, lubricant reduces friction which in turns reduces the amount of heat generation. Particularly in low cutting speed, shear angle increases due to the presence of lubricant which results in thinner cut chips [35]. However, for high-speed cutting, coolants are preferred in place of lubricant due to evaporation of lubricant oil at high temperature [36].

Coolant function is to cool the chip-tool interface and workpiece-tool interface at high-speed machining operations. Coolant has ability to prolong cutting tool life by maintaining the cutting zone temperature below thermal softening. Also, coolants

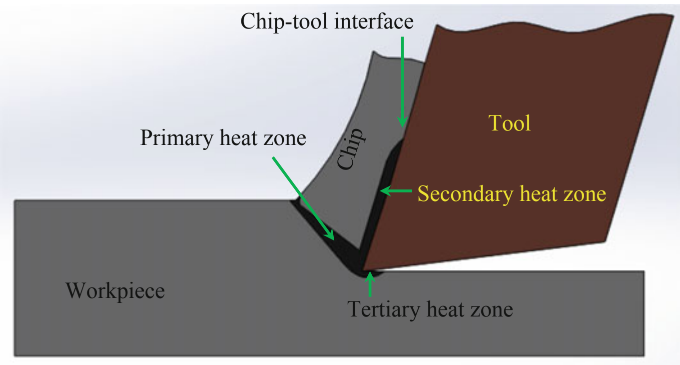


Fig. 2 Regions of heat generation in machining

are capable of reducing the tool wear (diffusion and adhesion). Water is considered as an ideal coolant for machining of non-ferrous alloys, particularly in high heat machining generation processes due to its excellent cooling capability [36].

Apart from the above two, cutting fluids also helps to flush away the generated chips and metal debris from machining zone to avoid tool clogging [37]. Chip evacuation capability of cutting fluids depends on its flow rate and viscosity. Cutting fluids having low viscosities are more capable of evacuating chips from machining zone as compared to cutting fluids having high viscosities [18]. Moreover, cutting fluids are able to reduce the required power for machining operations significantly. Therefore, cutting fluid should be chosen depending on various required properties as well as operating parameters and conditions [34].

2.2 Classification of Conventional Cutting Fluids

Initially, simple oils were considered as cutting fluids. Generally, oils were applied using brushes to cool and lubricate the machining zone. With the development of various hard materials and complex machining processes, different types of cutting fluids were required to meet individual machining demands. Cutting fluids are broadly categorized into three different classes as illustrated in Fig. 3.

2.2.1 Oil-based Cutting Fluids

Neat oils are also known as oil-based cutting fluids. They are generally derived from animal, vegetable or minerals. Among all, mineral oil based cutting fluids are most common in industries. Neat oils have good lubrication properties. Also, they have better anti-corrosion and anti-seizure characteristics, but they have poor cooling ability. Hence, they are susceptible to catch fire and results in the formation of smoke

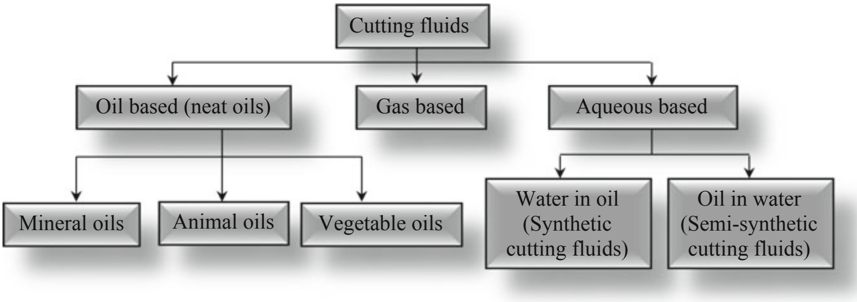


Fig. 3 Classification of conventional cutting fluids

[38]. Therefore, they are generally used for low-speed machining operations, where less heat is generated [18, 19].

2.2.2 Gas-based Coolants

Cutting fluids in the form of gases or cooled-pressurized fluids are categorized as gas-based coolants such as carbon dioxide, helium, nitrogen, argon or even air. These are generally considered as eco-friendly gas-based coolants. As these are in the gaseous state, they are highly anti-corrosive and have a high cooling ability as compared to other cutting fluids. However, they do not have any lubricating capacity. To overcome these problems, the gas-based coolant can also be applied along with a small amount of oils in the form of spray or mist. Combination of gas with small part of oil can be atomized and focused at machining zone. This application technique is known as minimum quantity lubrication (MQL) [39–42].

2.2.3 Aqueous-based Cutting Fluids

Soluble oils are also known as aqueous-based cutting fluids. Generally, these oils are mixed with water to form an emulsion with the help of emulsifiable substance before its use [33]. An emulsifier helps proper dispersion of oil in water to form a stable emulsion [18, 19]. Due to the presence of water in emulsion, it has excellent cooling properties at the same time oil present in the emulsion improves corrosion resistance. Emulsions are used for high-speed machining operations, where more heat is generated [43].

Synthetic Cutting Fluids
Synthetic cutting fluid is generally free from mineral oil and includes several performance enhancing additives. Also, it includes water in small proportion [43]. They have a transparent watery appearance with slight yellow or green in colour, which helps in good visibility during machining operations. Due to the presence of various performance-enhancing additives in synthetic cutting fluids, it has better corrosion resistance, lesser surface tension and water softening characteristics. However, it provides less lubricating effect as compared to other cutting fluids [36]. Hence, they can be used for machining operations where the main requirement it to cool machining zone.

Semi-synthetic Cutting Fluids
The main difference between synthetic and semi-synthetic cutting fluid is that later contains mineral oil. However, the former does not. Semi-synthetic cutting fluids are emulsions containing water as prime coolant and oil as secondary with various chemical additives to make it a highly effective lubricant. The concentration of water in these oils varies in the range of $50-90\%$ [44]. Both aqueous based cutting fluids have lower bacteria growth, corrosion rate and foul odour [45]. Table 1 shows the merits and demerits of various types of cutting fluids [12, 18, 19].

Table 1 Merits and demerits of various types of cutting fluids [12, 18, 19], with kind permission from Elsevier

Cutting fluids	Merits	Demerits
Neat oils	Better corrosion resistance and good lubrication	Susceptible to fire, smoke and mist, only for low-speed machining and low cooling ability
Soluble oils (Emulsions)	Good coolant and lubrication	Susceptible to bacterial growth and workpiece corrosion
Synthetic cutting fluids	Good microbial and corrosion resistance as well as better cooling	Contamination with other machine fluids, less stable by water hardness and foaming issues
Semi-synthetic cutting fluids	Good microbial resistance and corrosion control, less foam and mist issues, no flame or smoke issues and excellent coolant	Contamination with other machine fluids and poor lubrication

2.3 Ecological Aspects of Conventional Cutting Fluids

Ecological concerns call for the reduction of cutting fluids usage in metal cutting practice. Nowadays, it has become an essential objective in industry. Efficient utilisation of cutting tools in machining is an essential focus of researchers. The performance of the cutting tool depends on the process parameters and the cutting environment. Many times, cutting fluids are used to improve the workpiece surface finish and tool life. The fluids that are used to lubricate in machining contains potentially damaging or environmentally harmful chemicals constituents. The airborne particle of cutting fluids can be inhaled by operators that cause respiratory irritation, asthma, pneumonia, dermatitis and different kinds of cancers (oesophagus, colon, skin, lung, pancreas, etc.) [46, 47].

Repeated use of cutting fluids causes changes in its chemical composition. Changes occur because of tramp oil, contamination with metal chips and environmental effects. These contaminated cutting fluids are prone to bacteria growth. As cutting fluids are applied at the high-temperature zone, they also have tendency to form mist and smoke. Also, used cutting fluids disposal causes various detrimental effects on the environment. Due to these reasons, cutting fluid focus is changed from "cooling and lubrication" to renewability, biodegradability and sustainability [48]. Some other aspects of eco-friendly cutting fluids are non-toxic nature, energy saving, life cycle assessment, biomagnifications and bioaccumulability [49, 50].

Therefore, the concept of dry machining has the merits regarding non-pollution of the atmosphere and water, reduction of the cleaning and disposal cost, and no danger to health such as allergy and skin rupture, etc. As such, dry machining has become popular with regards to the safety of the environment as well as low production cost. However, sometimes the surface integrity of the finished product in dry turning is not superior as compared to wet turning. The concept of surface textures, minimal quantity cutting fluid, green and nano cutting fluids in turning seems to be a better alternative to conventional dry and wet machining [51–58]. Moreover, the combination of the above processes makes machining much more sustainable by reducing adverse environmental effects, associated costs and enhancing the operator's safety. Furthermore, it also improves machining performance and final workpiece surface finish.

2.4 Eco-friendly Cutting Fluids

As discussed in previous sections, conventional cutting fluids have various detrimental effects. Therefore, from the early 1990s, researchers and industrialist started focusing on the development of eco-friendly cutting fluids. Most important characteristics of eco-friendly cutting fluids are its biodegradability and sustainability.

In the presence of micro-organism (which are abundant in the atmosphere), biodegradable cutting fluids are vulnerable to break down. In its primary degradation, the recyclable substance will vanish from its original molecule and other substance such as biomass, hydrogen and CO_2 will degrade during ultimate degradation. Out of both, ultimate biodegradability is considered as a measure for biodegradability [59, 60]. Further, cutting fluids sustainability can be categorized in two different ways; (a) its source of raw materials for production such as renewable materials or fossils, and (b) related to pollution caused during its use and after use (disposal) [61]. In terms of better biodegradability, vegetable-based oils and esters are highly desirable. However, for the best environmental sustainability, gaseous based coolants are preferable like water vapour as a coolant, cryogenic nitrogen or carbon-dioxide, pressurized gas, etc.

Lubricity and biodegradability of vegetable-based cutting fluids are better due to the presence of long fatty acids chains with a number of unsaturated double and triple carbon bonds. Long fatty acids chains such as triglycerides, linolenic, linoleic and oleic acids are highly biodegradable and all are present in most of the vegetable-based cutting fluids. Gajrani et al. [29, 60] compared primary and ultimate biodegradability of petroleum-based mineral oil with commercially available ecoline bio-cutting fluid. Results show that mineral oil was ultimately 18% biodegradable. However, bio-cutting fluids was 96% biodegradable due to the presence of long fatty acids chains mostly triglycerides. Typical chemical structure of triglycerides commonly found in vegetable-based cutting fluids is illustrated in Fig. 4. Typical chemical structure of oleic, linoleic and linolenic acids are shown in Fig. 5 [12].

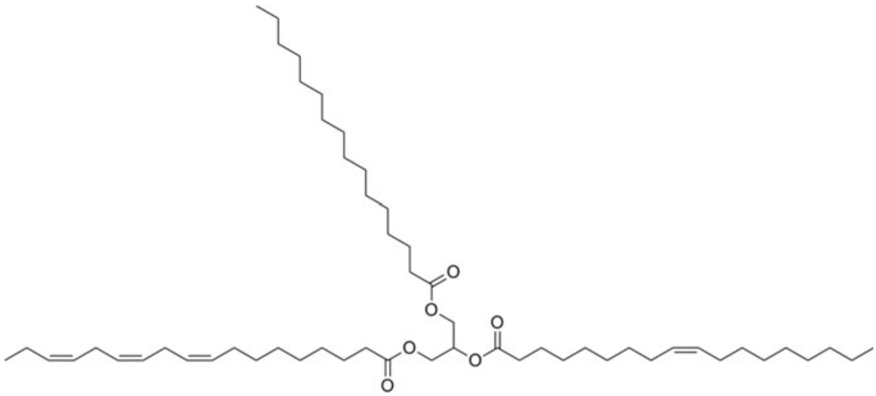


Fig. 4 Typical chemical structure of triglycerides

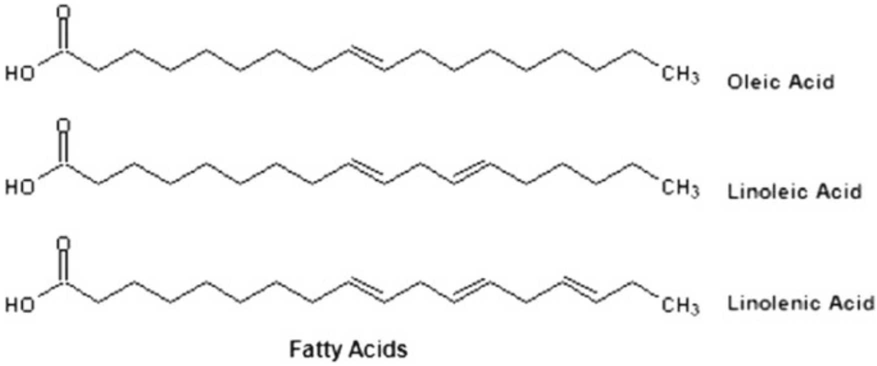
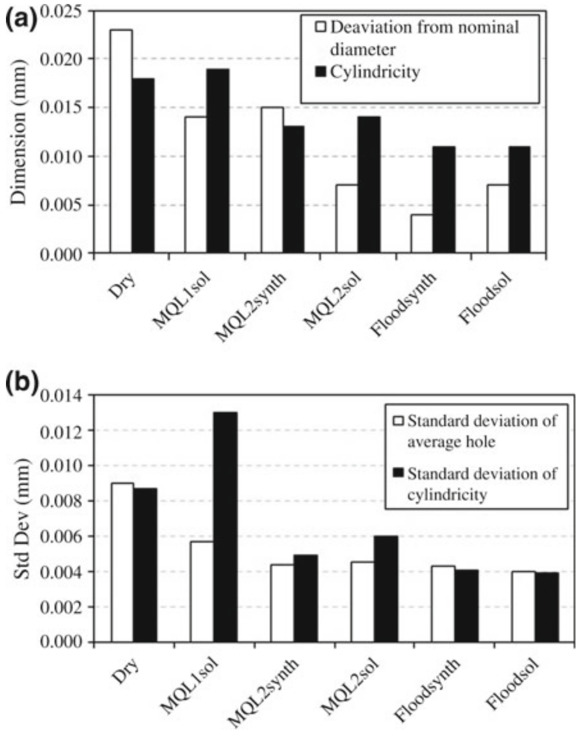


Fig. 5 Typical chemical structure of oleic, linoleic and linolenic acids [12] with kind permission from Elsevier

2.5 Cutting Fluid Application Techniques During Machining

Cutting fluid helps to reduce temperature and friction at the machining zone that leads to better workpiece surface integrity and tool life. However, workpiece surface integrity and tool life also depend upon the application techniques of the cutting fluids during machining. Further, some techniques are considerable better for few operations while other for different machining operations depending on the individual circumstances. In last two decades, new cutting fluids application technologies are also developed that aims to reduce overall consumption of cutting fluids without degrading the machining performance leading to more economical and efficient techniques as well as to improve the productivity [62]. Main conventional cutting fluids application techniques are (a) wet cooling (flood cooling), (b) high-pressure cooling, (c) cryogenic cooling and (d) mist cooling (minimum quantity lubrication)

Fig. 6 Workpiece dimensional accuracy and its standard deviation with various cutting fluid application techniques [63] with kind permission from Elsevier



2.5.1 Wet Cooling (Flood Cooling)

From the last century, flooding or wet cooling is most commonly used cutting fluid application technique for coolants. In flood cooling, a continuous stream of coolant is focused at the machining zone for cooling chip-tool interface during machining [36]. Consumption of coolant is highest for flood cooling among all techniques. A typical range of coolants flow rate for single point cutting tool operation is around 10L/min and for multiple points cutting tool operation is around 225L/min/per tooth [43]. As per Schey [35], flood cooling should be applied from tool clearance face for better cooling performance. Jayal et al. [63] performed blind hole drilling operation on A390 aluminum alloy using various cutting fluid application techniques and results show that flood cooling was best among all in terms of workpiece dimensional accuracy as illustrated in Fig. 6.

In 2014, Imran et al. [64] investigated the surface integrity and wear mechanism during micro-drilling of Inconel 728 under wet cooling and compared results with dry machining. After investigation using transmission electron microscope (TEM) and scanning electron microscope (SEM), they concluded that large-scale deformations along with high discoloration density having nanocrystalline grain structures are visible under wet machining conditions as compared to dry machining. Figures 7

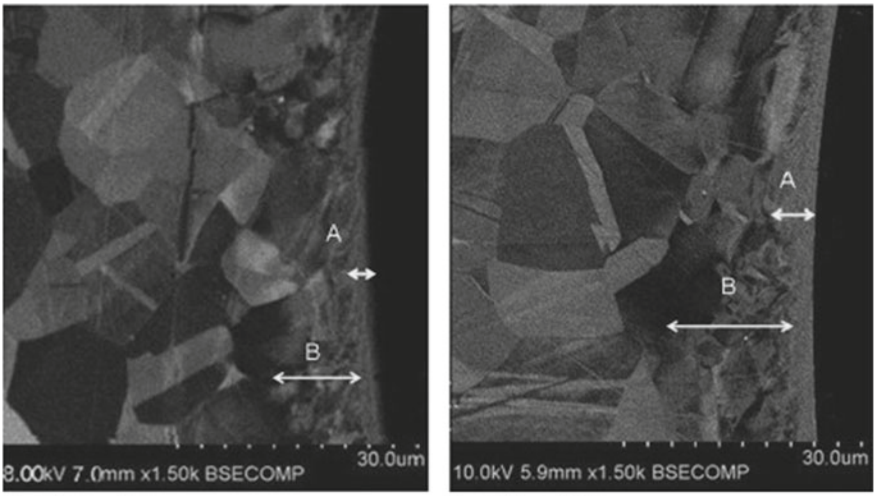


Fig. 7 Comparison of dry and wet drilling (micrograph of drill beat edge) [64] with kind permission from Elsevier

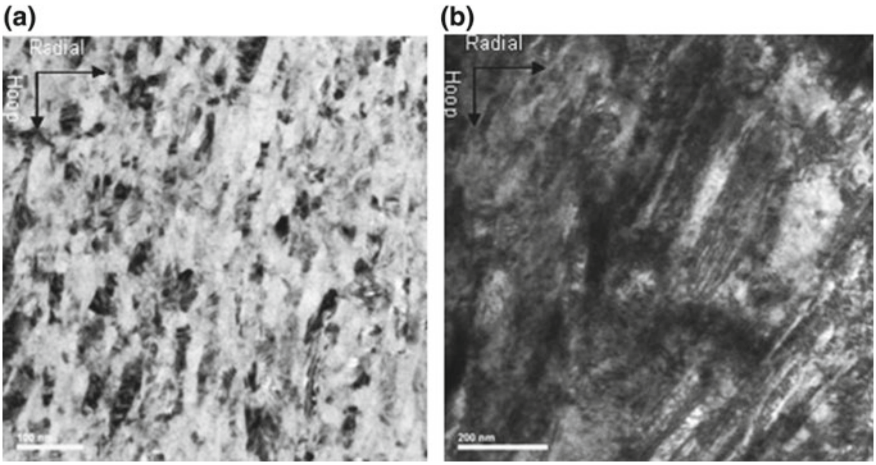


Fig. 8 Fine grain structure layer for **a** dry and **b** wet machining [64] with kind permission from Elsevier

and 8 illustrate the SEM and TEM images of dry and wet micro-drilling, respectively [64]. Figure 9 illustrates the tool wear mechanism sequence during micro-drilling under dry and wet cooling machining [64].

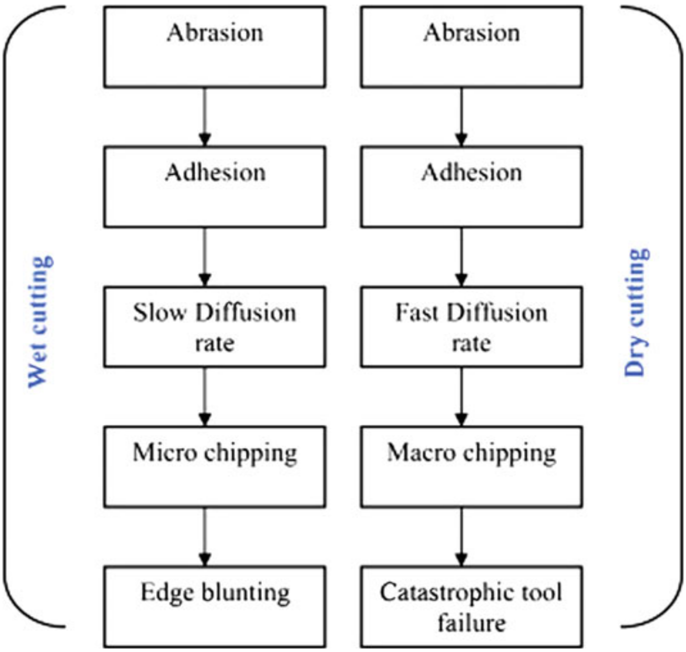


Fig. 9 Tool wear mechanisms sequence for dry and wet machining [64] with kind permission from Elsevier

2.5.2 High-pressure Cooling

Generally, this technique is used to increase the heat removal from the machining zone due to high pressure, which allows better penetration of cutting fluids at the machining zone. Specially designed nozzles are used to deliver high pressurized fluids to sustain pressure. The pressure varies in the range of 5.5–35 MPa. Apart from better cooling ability, it also improves tool life and reduces tool-chip interface contact length as high pressurized fluids forces chips away from the tool surface [62]. However, there are few limitations to this technique such as high-pressure jet may damage workpiece surface or tools, which are brittle in nature (especially ceramics) [43].

During turning of AISI 316 austenitic stainless steel, Naves et al. [65] investigated the tool wear under the influence of high pressurize fluids. The pressure of the cutting fluids was varied from 10 to 20 MPa (in the interval of 5 MPa). Machining experiments were carried out and it was observed that tool wear was least with high pressurize cooling (15 and 20 MPa) compared to dry and wet cooling techniques as illustrated in Fig. 10 [65].

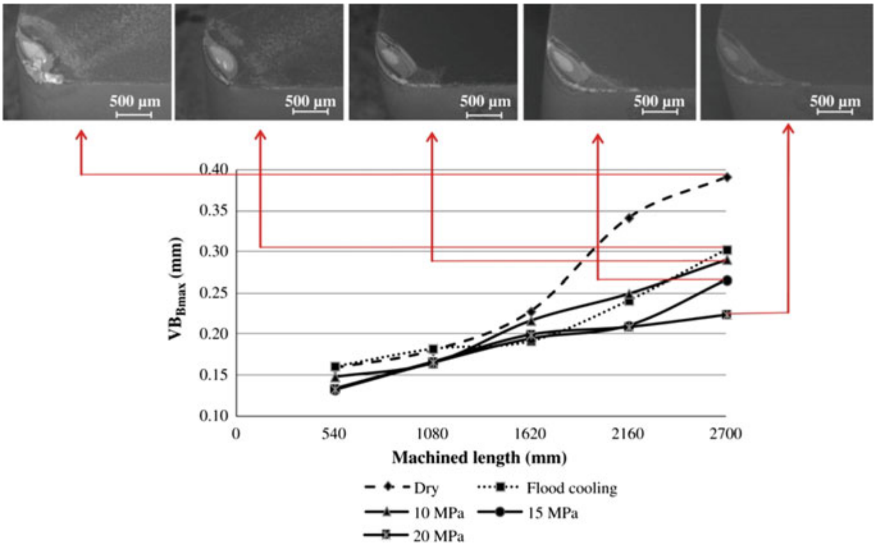


Fig. 10 Variation of tool flank wear with respect to machined length under the various cutting environment (5% concentration of cutting fluid) [65] with kind permission from Elsevier

2.5.3 Cryogenic Cooling

In this cooling technique, gases such as helium and nitrogen are used as a coolant. As both nitrogen and helium are inert gases, they are eco-friendly. Generally, these gases are injected at the chip-tool interface in liquefied form around −200 °C to cool the machining zone. These liquid gases reduce the machining zone temperature by absorbing heat and quickly evaporate in the form of gas [43]. Moreover, after machining using cryogenic cooling, chips are free from oil residue. Therefore, they can be recycled without any additional cleaning process.

In general, machining forces required with cryogenic cooling are less as compared to dry machining due to its cooling properties and ability to reduce friction at the chip-tool interface. However, the pressure and flow rate of cryogenic coolant is very crucial. If machining zone is overcooled, required cutting force will be more due to workpiece embrittlement. Cryogenic cooling is more useful at a low cutting speed. However, with the increase in cutting speed, contact of chip-tool will be plastically dominant which obstruct the passage of cryogenic fluids and reduces its efficiency.

Sharma et al. [62] have reported that under the influence of cryogenic coolant, the tool wear such as diffusion, adhesion and abrasion were reduced and tool life increased. Babic et al. [66] have mentioned that while operating with a high temperature, the operation accuracy of cryogenic cooling is inadequate. In another study, the influence of liquid nitrogen was compared with wet cooling during turning operation. Results confirmed that turning with liquid nitrogen significantly reduces flank wear, cutting force and workpiece surface roughness as compared to wet cooling

[67]. Similarly, Wang et al. [68] reported 200 and 300% improvement in workpiece surface roughness and tool life, respectively during cryogenic machining of tantalum as compared to conventional machining.

2.5.4 Mist Cooling (Minimum Quantity Lubrication)

In this technique, a combination of cutting fluids with pressurized air is applied at the machining zone in the form of mist or spray. This technique is commonly known as MQL and also known as micro-lubrication as well as minimum quantity cutting fluids (MQCF) [60]. The atomised mists with fluid droplets are effective to provide cooling effect [35]. Also, the mist is able to reach at most of the places unlike flood cooling [43]. Further, machining using the MQL technique is known as one of the cleaner production method [69]. Machining using MQL may reduce the amount of cutting fluid in the range of one-thousandth to ten-thousandth as compared to wet cooling [43]. Further, if the biodegradable cutting fluid is used as cutting fluid with MQL technique, the sustainability of overall process increases further [13]. A typical MQCF experimental setup is shown in Fig. 11 [60].

An eco-friendly cooling method known as cold water mist jet (CWMJ) was applied to reduce machining zone temperature while turning of titanium alloy [70]. Results of CWMJ were compared with flood cooling and cold air jet concerning cutting temperature and tool flank wear as illustrated in Figs. 12 and 13 [70]. It was observed that CWMJ cooling effect was much better compared among all which can be comprehended by lesser cutting temperature and tool flank wear.

In another study, only mixture of air and water were applied in the form of a mist to cool grinding zone for removal of ecological hazards (cutting oils) and to make the process more economical [66]. Authors concluded that this water and air combination has ability to cool and the maintain shape of grinding wheel as compared to conventional cutting fluids with existing application techniques. Among all, best results were obtained with two mist nozzles (each at front and back).

2.6 Role of Eco-friendly Cutting Fluids and Cooling Techniques on Machining Performance

In previous sections, various types of cutting fluids and cooling techniques are discussed. Among all MQL with a combination of biodegradable cutting fluids are generally accepted as a better eco-friendly and sustainable machining method [43]. In a study of plain turning, three different cooling techniques (MQL, dry and wet) were experimentally compared in terms of workpiece dimensional deviation and cutting temperature during machining of AISI 1040 steel. Results confirm that MQL environment was able to improve the workpiece dimensional accuracy and reduce the chip-tool interface temperature as illustrated in Fig. 14a, b [71].

Fig. 11 Minimum quantity cutting fluid experimental setup [60] with kind permission from Elsevier

In another study, machining performance of vegetable-based oils was compared with three different cutting fluids such as mineral, hydrocracked and synthetic oils using MQL technique during grinding of Al_2O_3 ceramic. Obtained results show that hydrocracked-based oil is better in terms of workpiece surface finish. However, synthetic oil uses low specific energy during rough grinding [72].

Itoigawa et al. [73] investigated the friction coefficient and chip-tool contact length during intermittent turning of aluminium alloy under dry, flood, MQL and OoW (Oil film on water with MQL) environments. The difference in MQL and OoW-MQL is that later contains a mixture of water and oil as cutting fluids. However, former only has oil. Authors claim that OoW-MQL performance is better as compared to other two due to better cooling as well as lubricating properties of OoW-MQL as compared to the only MQL with oil. Figures 15 and 16 illustrates the variation of friction coefficient and chip-tool contact length under different machining environment.

Gajrani et al. [29, 60, 74] compared the performance of mineral oil and bio-cutting fluid in terms of their biodegradation, storage stability, anti-corrosion, rheological,

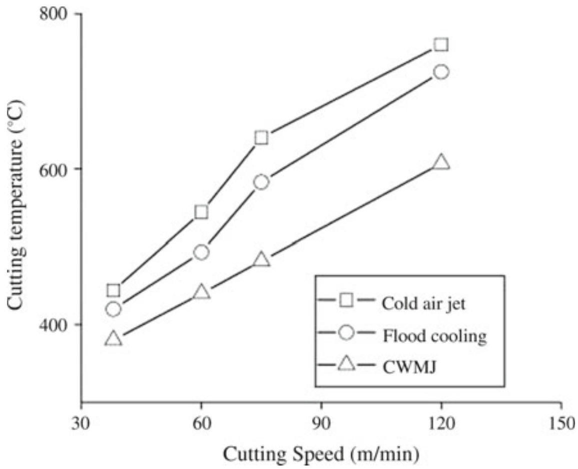


Fig. 12 Variation of cutting temperature using various cooling techniques [70] with kind permission from Elsevier

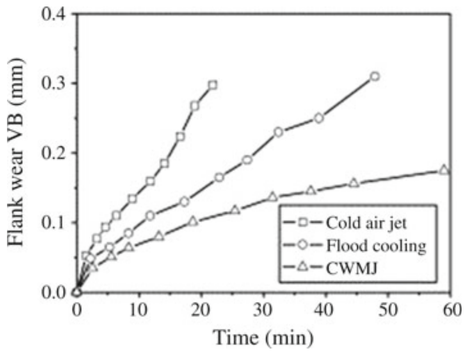


Fig. 13 Variation of tool flank wear using various cooling techniques (cutting speed = 38 m/min) [70] with kind permission from Elsevier

thermal and hard machining performance under flood and MQL environment. Results show that bio-cutting fluid is far superior to mineral oil in terms of their biodegradation, storage stability and anti-corrosion properties. Also, BCF with MQL reduces tool-chip interface length and reduces machining forces. In another study, Gajrani et al. [58] developed vegetable based green cutting fluid and conducted hard machining experiments on hardened AISI H-13 steel under dry, flood and MQL environment. Results show that GCF reduces more tool-chip interface friction coefficient and surface roughness of workpiece under MQL environment as compared to dry and flood cooling.

Further, another study compared four different cutting fluids consisting of sunflower oil-based cutting fluids with and without surfactants as well as commercial vegetable and mineral oil [75]. During turning of AISI 304 steel under MQL envi-

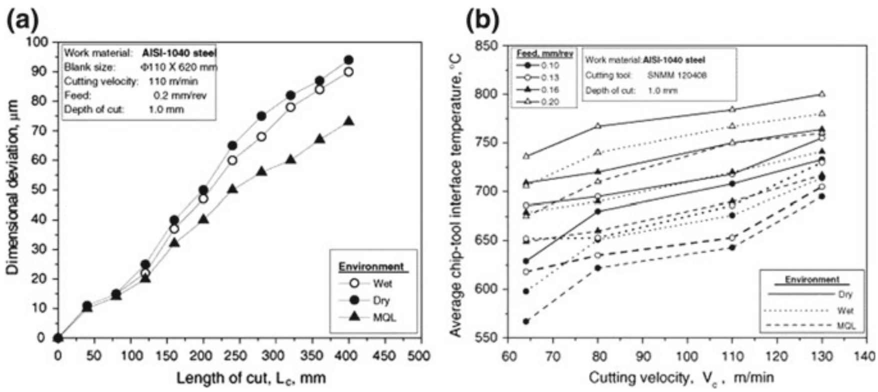


Fig. 14 Effect of MQL on **a** workpiece dimensional deviation and **b** chip-tool interface temperature [71] with kind permission from Elsevier

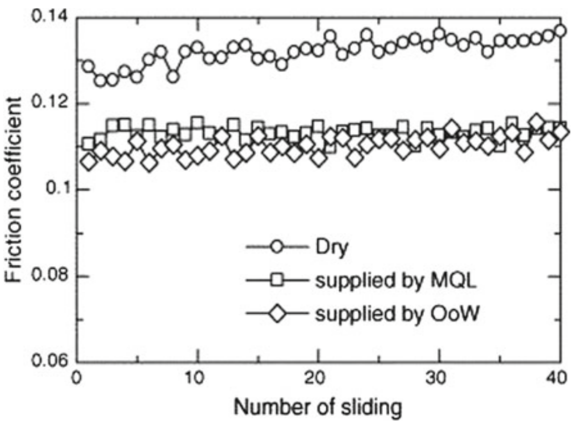


Fig. 15 Variation of friction coefficient during intermittent turning under different machining environment [73] with kind permission from Elsevier

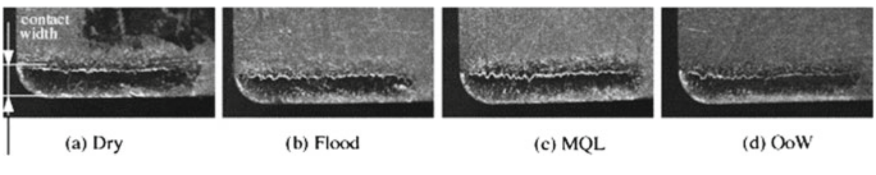


Fig. 16 Variation of chip-tool contact length after intermittent turning under different machining environment [73] with kind permission from Elsevier

ronment, sunflower oil-based cutting fluids show best workpiece surface roughness among all. Paul and Pal [76] investigated the effect of neem, kajrana and mineral oil and found that neem oil performance is better among others for reducing the cutting temperature. Gupta and Laubscher [77] presented a review on sustainable machining of titanium alloys and they also mentioned that MQL has shown promising results during machining of difficult-to-cut materials. Afterwards, few researchers have dispersed nanoparticles in the vegetable based cutting fluids to enhance its thermal conductivity. Results show that nanofluids significantly reduce cutting temperature, machining forces, tool wear, surface roughness of workpiece and also improves tool life [78–83].

3 Sustainable Machining for Future

Petroleum-based mineral oils are non-renewable and have detrimental environmental effects as well as they are harmful for operators. Therefore, the trend of cutting fluids shifted from petroleum-based cutting fluids to biodegradable and renewable vegetable-based eco-friendly cutting fluids. They are far better than mineral oils in terms of machining as well as eco-friendly nature. Also, with MQL vegetable based cutting fluids have shown a lot of potential. However, vegetable-based cutting fluids also have some limitations. They are costly and more preferred for low to medium cutting speed. Also, most of the vegetable-based cutting fluids have low oxidative and thermal stability as well as their production may raise prices of agriculture product. A number of studies have already focused and confirmed that machining performance is better with vegetable-based cutting fluids and the amount of cutting fluid required with MQL is less. Now, the researchers need to focus on further reducing the quantity of cutting fluids or to entirely eliminate the cutting fluid usage by switching to dry machining.

Dry machining with micro/nano-textured cutting tools, coated cutting tools, self-lubricating cutting tools has shown enormous potential to reduce friction coefficient and to improve machining performance. Thus, future research needs to be focused on improving dry machining and to develop new materials that can able to machine difficult to cut material without cutting fluids to make it eco-friendly process.

4 Conclusion

Initially, this study focuses on the history, functions and classifications of cutting fluids. Afterwards, ecological and environmental detrimental effects of cutting fluids are discussed. Further, eco-friendly cutting fluids merits, demerits, advantages, biodegradability, renewability, etc. are discussed in length. Moreover, the role of eco-friendly cutting fluids and various applications techniques on machining performance are deliberated.

Vegetable based eco-friendly cutting fluids are mainly preferred due to its high biodegradability and renewability in nature. Also, they provide better machining performance as compared to mineral oil-based cutting fluids in most of the cases. However, still they have few demerits such as low oxidative, low thermal stability, high freezing point as well as high cost, which needs more focus in future.

Machining with cryogenic coolants shows promising results to improve machinability of difficult-to-cut material and also to reduce workpiece surface roughness. In most cases, machining with cryogenic coolants reduces chip-tool interface coefficient of friction, machining forces and improves tool life against adhesion and abrasion wear. However, overcooling may cause embrittlement of workpiece, which may affect adversely to the product quality.

MQL is a most promising technique to reduce issues of environment and if coupled with vegetable-based cutting fluids, it shows remarkable improvement in machining performance as compared to flood cooling.

Even though cryogenic, vegetable-based cutting fluids and MQL are not the generalised solutions, but they showed tremendous improvement in making machining more sustainable. Furthermore, dry machining is becoming more popular to address environmental and operator's health issues.

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