A Techno-Health Study of the Use of Cutting Fluids and Future Alternatives

Alborz Shokrani*, Vimal Dhokia, and Stephen T. Newman

Department of Mechanical Engineering
University of Bath
Bath, BA2 7AY, United Kingdom

Abstract

The health issues associated with exposure to cutting fluids is an increasing concern among occupational health researchers. However, this issue has been overlooked in manufacturing enterprises from engineering prospective. The aim of this paper is to provide a multi-disciplinary review of the health issues related to the use of cutting fluids in machining companies and provides some alternative solutions through a series of case studies. The studies indicated that minimum quantity lubrication, biostable oils, cryogenic machining and dry machining are potential alternatives to traditional flood cooling with potential to improve machinability.

1. Introduction

Coolants/Lubricants (CLs) also referred to as metal working fluids and cutting fluids are liquids used during metal shaping operations to improve the machining performance in cutting or shaping of materials. They are usually straight oil or water-based fluids which are used to cool and lubricate the cutting zone and remove the chips [1, 2]. Based on the first law of machining (Makarow's law), the highest machinability is achievable at a certain temperature known as the optimum cutting temperature θ_{opt} where the ratio of cutting tool hardness to workpiece material hardness is at its peak [3]. Thus, the highest machinability is achievable when the cutting temperature is close to the optimum cutting temperature and using cutting fluids is one of the techniques to prevent overheating and maintain cutting temperature close to the optimum cutting temperature [3].

Although the early use of water as a cooling medium dates back to the 16th century [4], using coolants as a technique to improve machinability is based on the studies conducted by Taylor [5] in the late 19th and early 20th century in machining steel alloys. Cutting fluids can help improve machinability through different mechanisms. Using coolants can prevent the cutting temperature going beyond the heat softening temperature of the cutting tool material and thus improve tool life and prevent heat induced wear such as diffusion and adhesion. In addition, they can lubricate the cutting surfaces and prevent friction thus, reducing mechanical wear and the heat generation as a result of friction. Despite these, at high cutting temperatures, local evaporation of cutting fluids can form hot vapour barriers, preventing effective heat dissipation from the cutting zone. Therefore, the generated heat accumulates at the cutting zone and results in a further increase in temperatures [3]. To cope with this, different chemicals and additives have been added to the advanced cutting fluids to fulfil the requirements for machining different materials.

Having a wide range of characteristics, there are different methods of classifying traditional cutting fluids. The most common method of categorising traditional cutting fluids however is based on their solubility in water [1]. Based on this characteristic, traditional cutting fluids have been defined into two categories of water-miscible and neat or straight oil. Water-miscible cutting fluids consist of three types of (i) soluble oil, (ii) synthetic fluids and (iii) semi-synthetic fluids. Soluble oil cutting fluids contain mineral oil and emulsifiers which allow the oil to be dispersed into water whilst synthetic fluids are oil-free solutions made of chemicals and may contain organic or inorganic substances. Mineral oil and chemical additives together are used in semi-synthetic cutting fluids to provide both characteristics of soluble oils and synthetic fluids. Straight or neat oil cutting fluids are mineral-oil based compounds which often contains chemical substances such as extreme pressure chemicals, viscosity index modifiers and friction modifiers in order to improve their machining characteristics [1].

* Corresponding author: Tel.: +44 (1225) 386934; Fax: +44 (1225) 386928; E-mail: a.shokrani@bath.ac.uk

The combination of water and oil in water-miscible cutting fluids provides a reach environment for bacteria to culture. In addition, mineral oil and some chemical substances in both water-miscible and straight oil cutting fluids are also known as sources of health hazards to human. Next chapter provides an in-depth understanding of the potential health hazards of exposure to cutting fluids in workers.

2. HEALTH ISSUES:

Recent studies on work related disease have raised questions on the safety of workers using cutting fluids in machine shops. In 2007, a report by the HSE WATCH committee [6] identified a priority to the health issues related to respiratory exposure to water-based cutting fluids. The report raised health concerns due to the heavy contamination of metalworking fluids by bacteria, endotoxin and other allergens related to the dead organisms. The report identified that almost 240,000 tonnes of water-based cutting fluids are consumed in the UK annually and approximately 50,000 workers are exposed to cutting fluids. This figure increases to 1,200,000 workers in the USA being exposed to metal working fluids including water miscible and straight oil coolant/lubricants [7, 8]. Workers can be exposed to cutting fluids by direct skin contact or through inhalation of mist generated during machining operations. The majority of the outbreaks reported were studies conducted in the USA from automotive or aeronautical industries with central coolant system [9]

2.1. RESPIRATORY DISEASE:

One of the common problems associated with the use of cutting fluids is respiratory diseases such as Occupational Asthma (OA), Hypersensitivity Pneumonitis (HP) and Bronchial Hyper-Responsiveness (BHR) [10]. The most common respiratory symptoms as a result of exposure to cutting fluids aerosols have been identified to be dry cough, phlegm, wheezing, soar and hoarse throat, chest tightness, short breath, sore/red eyes and fever/chill [2]. These can be due to the bacterial/fungi contamination, existence of endotoxin in the cutting fluid and/or the existence of chemicals and additives in the cutting fluids [1, 2, 11]. Gordon et al. [11] identified that the effect of microbial contamination is greater than that of chemical composition of the cutting fluids. Endotoxin is an important structural component of the outer wall of Gram-negative bacteria that may typically exist in cutting fluids and can cause immunotoxicological responses [6, 12]. In a review, Gordon et al. [11] noted that endotoxin plays an important role in toxicity of cutting fluids and their adverse effects on health. They found that exposure to straight oil cutting fluids, where no endotoxin exists, the toxicity is dependent on the chemical composition of the fluid. They noted that synthetic and semi-synthetic water-based cutting fluids are the most toxic due to the existence of endotoxin [11]. In a case study, Gorny et al. [13] found that different types of Gram-positive bacteria exist in the aerosol of both water-based and straight oil cutting fluids using different measurement techniques.

The most notable incident in the UK concerning metalworking fluids is commonly known as Powertrain Occupational Respiratory Disease outbreak where more than 100 shop floor workers were diagnosed mainly with HP and OA [10]. This case is known as the largest outbreak in Europe [14]. Powertrain Limited is a Phoenix Venture Holding Limited company based in Longbridge, Birmingham, UK. The company produces engine components from aluminium alloys and cast iron and uses water-based fluids for different processes ranging from metal cutting to washing [10]. In an investigation, 87 workers were diagnosed with occupational lung disease comprising of HP, OA and humidifier fever with 12 workers diagnosed with more than one condition [14]. An immunology study of the diagnosed workers and analysis of samples taken from the sump oil concluded that there is a link between bacterial contamination of water-based fluids used in the factory and HP/OA cases [10].

A study in a car engine manufacturing plant in France [15] indicated that 84% of samples taken from used MWF had microbial contamination. Mycobacterium immunogenum, a gram-positive bacteria associated with HP, has been found in 40% of the contaminated samples. Similar observations have been reported by other researchers globally [16-19].

2.2. DERMATITIS:

Different types of occupational skin disease are also, or suspected to be, associated with the use of metal working fluids in the form of coolants and lubricants either through skin contact or absorption. The most common type of skin disease associated with use of coolant/lubricants is dermatitis [19] and metal working fluids are ranked as the first cause of hand dermatitis [20]. A study among the machinists in Finland between years 1992 to 2001 revealed that metal working fluids and their chemical ingredients were the most common cause of occupational allergic contact dermatitis. The most common chemical allergens have been identified to be formaldehyde, ethanolamine and colophony [19].

In an study, Henriks-Eckerman et al. [21] analysed the chemical components of 17 different types of metal working fluids. Their study revealed that different types of chemicals commonly known as allergens can exist in the chemical component of metal working fluids. The following chemicals have been found in all or some of the tested metal working fluids: (i) formaldehyde, (ii) alkanolamines, (iii) benzisothiazolinone, (iv) octylisothiazolinone, (v) iodo propynyl butyl carbamate (IPBC) and (vi) colophonium [21]. Another study [22] identified monoethanolamine (MEA), colophony/abietic acid, fragrance mix and biocides as the most common sources of occupational skin dermatitis amongst workers in Germany [22, 23]. A study on the effects of exposure to metal working fluids on the workers of an aerospace engine manufacturing company indicated that workers who are exposed to metal working fluids are significantly more likely to be diagnosed by dermatitis [8]. They [8] reported that most of the cases have been observed on wrist and forearm which is due to direct skin contact with metal working fluids. Similar observations and conclusions have been reported by other researchers [24-27].

2.3. Cancer:

Machining coolants and lubricants are strongly believed to cause different types of cancers such as skin, bladder lung, stomach and colon/rectal [28, 29]. In addition, they are suspected to be related to prostate, breast, pancreatic and esophageal cancers [28, 30, 31]. A study by Agalliu et al. [31] on the cohort workers of General Motors Co. in a 25 years period, indicated a strong relation between prostate cancer and exposure to oil-based (water miscible and straight oil) cutting fluids. In another study [29], linear correlation between risks of colon cancer has been found with cumulative exposure to straight oil cutting fluids with a 15 year lag and a maximum hazard ratio of 3.2 at 40 mg/m^3year. A study in Northern New England indicated that male workers who have been exposed to metal working fluids have a significantly higher chance of developing bladder cancer [32]. One of the first studies [33] on the effect of exposure to soluble and synthetic cutting fluids and cervical cancer in female workers reported that no statistically significant correlation has been found. However, they concluded that exposure to metal working fluids may play a role in developing cervical cancer.

3. Alternative Solutions to Traditional Coolants and Case Studies:

3.1. Dry Machining and Minimum Quantity Lubricant:

Minimum Quantity Lubricant (MQL) is a technique in which a small amount of lubricant is delivered into the cutting zone by the means of pressured air. The lubricant evaporates in contact with cutting zone resulting in reduced cutting temperatures [34, 35]. As the use of cutting fluids as compared to wet machining is significantly reduced, Klocke and Eisenblatter (1997) classified dry machining and MQL together. In MQL, the negative effects of cutting fluids on health and environment are reduced significantly as the cutting fluid is not circulating through the system. However, the airborne particles that occur as a result if spraying lubricants into the atmosphere can be a potential health hazard in the workshop. Therefore, good insulation of the machine tool is a necessity in order to prevent possible contamination of the shop floor from airborne particles.

The best approach in eliminating the adverse effects of cutting fluids on health and environment is to cease using them altogether. This technique is more commonly known as dry machining. In a paper by Sreejith and Ngoi [36], dry machining is referred to as ‘the machining of the future’ as it eliminates cutting fluids from machining and reduces the manufacturing costs significantly whilst it has the potential to improve machinability.

A case study has been conducted in order to identify the possibility of dry machining of Ti-6Al-4V titanium alloy. The selected machining operation was end milling using solid carbide cutters under two machining environments of dry and wet. The study consists of two machining trials based on a one-factor-at-a-time experiment by changing the machining environment and keeping other machining parameters constant at two levels. The machining parameters used for these two machining trials are shown in table 1.

Two machinability indices of tool wear and surface roughness have been selected as control parameters. In addition, power consumption of the machine tool has been monitored during the experiments. Table 2, illustrates the surface roughness and tool wear of cutting tools after machining 600 mm^3 of removed material. Figure 1 illustrates the cutting tools used in experiment 1 after machining operations. The figure shows that the tool wear is almost equal for both tests irrespective of machining environment.

Table 1. Cutting parameters used for dry and wet machining of titanium alloy.

Parameter	Experiment 1	Experiment 2
Cutting speed (rpm)	796	3050
Feed rate (mm/min)	71.5	274.5
Depth of cut (mm)	1	1

Table 2. Measurement of surface roughness and tool wear for machining titanium.

Machinability metric	Experiment 1		Experiment 2	
	Dry	Wet	Dry	Wet
Surface roughness (Ra)	1.07	2.18	1.11	0.98
Tool wear (µm)	16	18	29	28

A comparison of the surfaces in experiment 1 indicated that the sample produced in dry machining has significantly lower (50%) surface roughness than the one from wet machining. Surface profilometery of the samples machined at higher cutting speeds (experiment 2) indicate that the surface roughness of both was almost similar. Analysis showed that the tool wear in dry machining is worn almost identical with tool wear observed in wet machining. These two experiments revealed that by conscious selection of cutting parameters, it is possible to eliminate the use of cutting fluids without compromising machinability whilst reducing adverse health effects and power consumption as shown in figure 2. In fact, by monitoring the power consumption of the machine tool, it has been found that dry machining can save up to 40% in power consumption reducing it from 2246w to 1367w for experiment 2 (figure 2). The average power consumption in experiment 1 was 2186w in wet machining which has been reduced to 1303w in dry machining by eliminating the coolant pump (40% reduction).

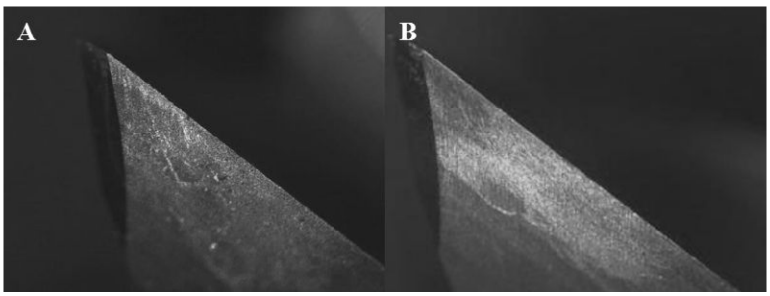

Figure 1. Cutting tools used for experiment 1 A) dry B) wet.

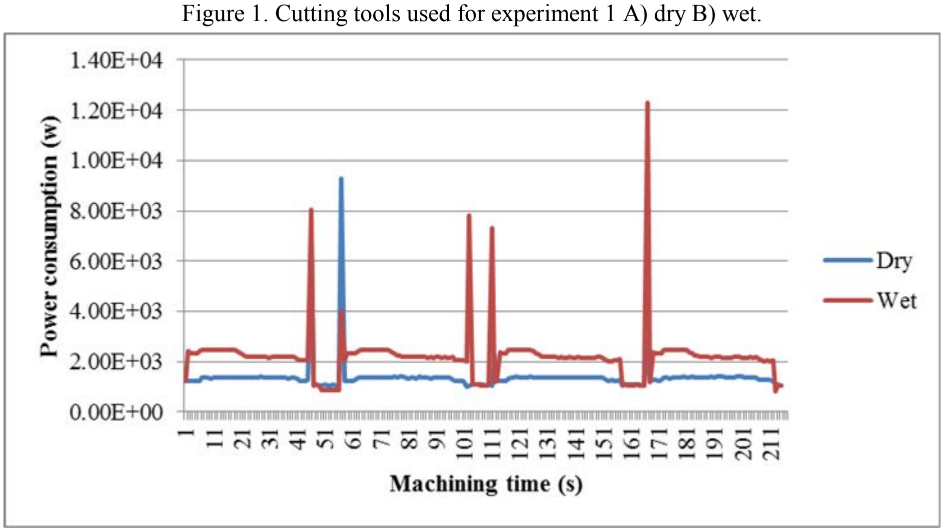

Figure 2. Power consumption of machine tool in dry and wet machining of titanium alloy in experiment 2.

3.2. Vegetable oil biostable cutting fluids:

Using vegetable oil as lubricant is another environmentally friendly alternative to straight oil [37]. The long polar fatty acid structure of triglyceride in vegetable oils provides good lubrication properties favourable for machining operations. In this method a vegetable oil such as grape seed, sun flower, soybean, coconut, etc. mixed with other chemicals are replaced with straight oil lubricants. There are reports stating that in some cases vegetable oils without additives have outperformed mineral oil based lubricants [37].

In a case study at Renishaw Plc, UK, an organic compound based on grape seed oil has been replaced with straight oil lubricants in turning operations of AISI 303 stainless steel. Improved tool life has been identified as one of the main advantages of using this lubricant compared to traditional straight oil lubricants. In addition, lower maintenance costs and zero bacterial growth have been reported as the other main advantages of using vegetable oil-based cutting fluids. Furthermore, no health issues and allergic reaction have been observed in workers who were in contact with the vegetable oil. One of the main problems in using grape seed lubricants is the relatively low flash point of the substance. The smoking point of grape seed oil is 216°C and at temperatures higher than this, there is a risk of ignition. This is particularly important as cutting temperatures above 216°C is considerably easy to reach, particularly in machining difficult-to-machine materials. Thus, for safety reasons, each machine tool is equipped with a fire detector and a fire extinguisher.

3.3. Cryogenic machining:

Using liquefied gases such as liquid nitrogen in machining operations, termed as cryogenic machining, has attracted significant research over the past decade mainly due to the capability of enhancing the machinability of difficult-to-machine materials [38]. In this method, a controlled flow of liquid nitrogen is delivered into the cutting zone. The super cold cryogen freezes the cutting tool and workpiece material and thus modifies their material properties. In addition, it absorbs the generated heat at the cutting zone and evaporates. Since nitrogen forms almost 80% of the air, it is generally considered as an environmentally friendly option with no significant health issues. The only noticeable health issues related to the use of liquid nitrogen are cold burns as a result of direct skin contact with super cold fluid, oxygen deprivation and nitrogen narcosis. This raises the requirement for personal protections for workers and oxygen monitoring facilities.

In a case study, 6061-T6 aluminium alloy has been tested for potential use of cryogenic machining in end milling operations. Two machining trials have been conducted using cryogenic and wet machining environments and the surface roughness of the samples have been measured. The cutting parameters used for the experiments are provided in table 3.

Comparing the results obtained for each machining environment indicated that there is no significant difference between the surface roughness (Ra) of the samples produced under cryogenic and wet machining environments. The average measured surface roughness for wet machining has been measured to be 1.06 μm whilst it was 1.04 for cryogenic machining. Repeating the measurement procedure 5 times for each sample and performing statistical t-test, indicated that the difference is not statistically significant. Since the number of experiments was limited and the cutting tools were not significantly worn, no comparison for tool life was performed. Thus, further research is necessary to identify the effect of cryogenic cooling on tool life. Based on these observations and previous studies for other materials [39-41], it can be concluded that cryogenic cooling can be used as an alternative environmentally friendly technique to wet machining. However, since extremely low temperatures in cryogenic machining can modify the material properties of both workpiece and cutting tool, modification and optimisation of cutting parameters including cutting tools' geometries for cryogenic machining is recommended [38].

Table 3. Cutting parameters used for machining aluminium alloy.

Cutting speed (rpm)	8000
Feed rate (mm/min)	635
Depth of cut (mm)	2

3.4. OTHER APPROACHES:

There are a number of techniques which can be used to eliminate or improve the adverse effects of using cutting fluids in machining operations, however further studies are required to justify their effectiveness. These techniques can be identified as:

- Using pressured air to cool and blow the cutting chips away from cutting zone;
- Using bioconcept cutting fluids where harmless bacteria are used to prevent the growth of harmful bacteria;
- Chilling the cutting fluid reduces the bacterial and fungal growth rate. Controlled temperature can further improve the machining stability;
- Agitating the cutting fluid in order to dissolve air into the fluid helps reduce the bacterial growth rate;
- Filtration and extraction of air from each machine tool and preventing airborne particles from contaminating the workshop's atmosphere.

4. CONCLUSIONS AND FURTHER WORKS:

The aim of this paper is to raise awareness amongst manufacturing engineers and machinists about environmental and health issues related to the use of cutting fluids in material cutting operations. A cross disciplinary review of literature, indicated that there are significant correlations between exposure to cutting fluids and some health issues ranging from occupational asthma and dermatitis to cancer. The studies revealed that the health issues associated with cutting fluids is not limited to their chemical composition but also to the existence of endotoxin. Bactericides and fungicides are used to kill and control the growth of bacteria in cutting fluids which result in releasing endotoxin inside the cutting fluids.

A series of methods and technologies including case studies have been introduced as alternative methods for traditional wet machining. Case studies indicated that MQL, dry machining, using biostable coolant/lubricants and cryogenic machining are potential alternatives to traditional flood cooling. The case studies indicated that most of these techniques have no adverse effect on machinability and in some cases improve machinability in comparison to traditional wet machining.

Although these alternative techniques have been known for year, they have not yet been fully adopted in the industry. To the knowledge of the authors, this is mainly due to the lack of knowledge and confidence in using these techniques as an alternative to flood cooling. Thus, further research is necessary to compare the effects of the identified alternative machining techniques with traditional flood cooling.

In addition, it has been found that different cooling techniques should be used for machining different materials as they behave differently at different machining conditions. Therefore, further investigations are required to identify the pros and cons of each alternative technique and individual recommendations should be provided for different workpiece materials.

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