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RESEARCH

Tribological Considerations of Cutting Fluids in Machining Environment: A Review

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A B S T R A C T

The paper presents a review to highlight the tribological aspects of cutting fluids in machining environment. In this study, different machining processes viz. turning, grinding, drilling and milling have been considered with a special focus on grinding process. The cutting fluids are primarily used as coolants and lubricants in the various machining processes. Different cutting fluids and the health hazards associated with their use have also been represented in this research article. The paper also highlights the role of work materials and the cutting tool materials from tribology point of view. The literature revealed that the development of biocompatible cutting fluids, recycling of cutting fluids, cutting fluids for high temperature tribological applications, studying the wetability characteristics with addition of nanoparticles, etc. can be taken up as study in order to enhance the tribological properties of the cutting fluids.

1. INTRODUCTION

In today's competitive world, manufacturers and designers are under tremendous pressure to make the machining processes more and more efficient. With the development of new materials and the recent advancements in the cutting technologies, friction and wear are still the major issues in a material removal environment. However, these issues are addressed with the use of cutting fluids, which remove the heat generated during the machining operation and on the other hand, lubricates the two surfaces in order to decrease the amount of friction. The lubrication research cell of ASME has laid emphasis on the role of tribology in the areas of energy conservation. It has been observed that nearly 5.5 percent of U.S. energy consumption is used in primary metals and metal-processing industries, out of which 0.5 percent is conserved due to the tribological advancements made in the recent past [1]. The recent tribological developments during the last few years have led to a shift in the metal cutting technology. Tribology – the science of friction, wear and lubrication plays a significant role in the synthesis of materials with a greater focus on metal cutting processes [2]. This paper reviews some of the commonly used cutting fluids and the fluid application systems, which are in practice in a machining environment. In a metal cutting process, the tribological aspects to be considered in a machining process are area of contact, stress distribution factor, interfacial temperature, etc. Various research studies have been carried out in the area of tribology in machining systems [3-5]. The conventional approach for selecting a cutting fluid in a machining environment is actually on the basis of performance characteristics and also the economical factors. Various researchers have developed different cutting fluids for machining processes [6-9]. In these research studies, the researchers have taken into consideration mechanical performance and environmental impact as the parameters for a cutting fluid.

Owing to the global environmental consciousness among the end users and the stringent environmental legislations machinists are in search of cutting fluids which pose minimal threat to the environment without compromising the performance of these fluids [6]. Moreover the disposability of these cutting fluids is another challenge faced by the researchers as they contain hazardous waste in the form of chemical or toxic matter [10]. Hence an optimal cutting fluid with all the attributes is the need of the present times. This paper is structured in a manner that it focuses on the various types of the cutting fluids developed by researchers, work material considerations thereof, tool material considerations, health factors associated, non traditional cutting fluids and minimum quantity lubrication for various machining processes from tribological point of view.

2. CUTTING FLUIDS IN A MACHINING ENVIRONMENT

2.1 Role of Cutting fluids

The cutting fluids are primarily used for cooling and lubrication purposes in a metal cutting operation. Over the last century, water was used mainly as a coolant due to its high thermal stability and availability [11,12]. However, its use is being slowly replaced due to the corrosion aspects and also due to non-satisfactory lubrication characteristics. The development of cutting fluids which were oil based have also led to the use of cutting oils (lubricants) for machining purposes, with the addition of extreme pressure (EP) additives. In the present industry, the cutting fluids commonly used are water based emulsifiable oils and straight cutting oils. However, some semi-synthetic and synthetic based cutting fluids have also been developed to improve cooling and lubrication characteristics in a machining environment [13,14]. Various parameters play an important role in the selection of cutting fluids.

Owing to the increasing manufacturing costs, the present day designers and manufacturers are shifting from conventional cooling systems to new cooling systems [15,16]. However, a thorough knowledge of tribology in a machining environment is essential, and therefore the designers and manufacturers need to understand the tribo concepts in terms of heat removal, cooling, wear reduction, lubrication aspects, and corrosion aspects involved therein.

2.2 Types of Cutting Fluid

This section describes the various types of cutting fluids used in a machining environment.

Straight Cutting Oils: These type of cutting fluids are a combination oil-based extreme pressure additives which improve the performance characteristics of the base oil to perform the desired cooling and lubrication activities. Generally applied in un-diluted state, the characteristic feature of these cutting fluids is that they do not mix with water and therefore do not form an emulsion with water. Apart from exhibiting good lubrication properties, effective anti-seizure qualities, they offer good corrosion resistance [17]. However, at cutting speeds mist and smoke formation has been reported. These cutting fluids are best suitable for heavy duty machining operations and also in some grinding applications. The poor heat dissipation in case of high speed cutting restricts their use. The higher initial and disposal cost also is a limiting factor due to which straight cutting oils find application in the cases when other types of fluids are not viable.

Water Emulsifiable Oils: Also known as soluble oils, these cutting oils form an emulsion but are not completely soluble in water. These are oil based concentrates, which contain emulsifiers which permit them to mix with water and form an emulsion. To improve the lubrication characteristics, additives are also added as in case of straight cutting oils. These cutting oils also contain some rust and corrosion inhibitors. These fluids are characterised by the properties of better cooling efficiency, low viscosity, non-flammability and non-toxicity, ease of reclamation and low initial and disposal costs. However, they also offer low lubricity, mist formation. These type of cutting oils are the most commonly used oils in present day machining scenario including grinding operations [17-19].

Synthetic Fluids: These cutting fluids are the chemical fluids containing synthetic water-soluble lubricants, which provide the necessary lubrication characteristics. These cutting fluids also contain some rust and corrosion inhibitors, biocides, and surfactants but do not contain any oil. Synthetic fluids offer resistance to rancidity, have good cooling properties, low viscosity, non-toxicity, biodegradability, etc. However, when used in heavy duty applications often encounter the problem of insufficient lubricity. Various tribological investigations have revealed that synthetic fluids are an appropriate choice in the future. Another issue with the application of synthetic fluids in machining is the non-compatibility of grinding operations in a manufacturing system. Moreover, poor lubrication properties are the major cause of its non-compatibility when synthetic fluids as coolants are used.

Semi-Synthetic Fluids: These cutting fluids contain up to 25 % of oil which is added to the concentrate solution. An important characteristic of these fluids is that upon dilution with water, they form a very fine emulsion. To improve the lubrication characteristics, oil is added. The issues related to the use of synthetic fluids led to the development of semi-synthetic fluids.

Cryogenic Coolants: Another improvement in the cutting fluid technology is the development and use of cryogenic fluids. Apart from thermal and environmental benefits cryogenic fluids offer better wear reduction capabilities. Having a temperature of the order of $-196\ ^0C$, these fluids are used primarily in difficult-to-machine materials, chip formation and chip breaking being the major issues associated with them [20,21]. The use of liquid nitrogen as a cutting fluid involves applications where it acts as a coolant to the tool, which has internal channels through which, liquid nitrogen is supplied under controlled pressure.

Dhar et al. have investigated the cutting temperature, tool wear, surface roughness in case of machining steel by using liquid nitrogen as the cutting fluid wherein significant improvement in the surface finish and tool wear has been reported [22]. Stanford et al. carried out a similar investigation on the turning operation of a plain carbon steel by using liquid nitrogen as a coolant. In this study authors have reported 55 % reduction in the flank wear [23]. The use of liquid CO_2 as a cutting fluid has been reported in various research studies [24,25] wherein reduction in the tool wear and oxidation wear has been observed [25]. The use of CO_2 as a coolant has resulted in doubling the tool life in case of machining of titanium alloys [24]. Jerold et al. have observed that the use of liquid CO_2 as a coolant results in better tool life as compared to the liquid nitrogen [26]. It is clear from the reviewed literature that Liquid nitrogen and Liquid CO_2 have been used as cryogenic fluids however the studies on other cryogenic fluids like liquid argon , liquid helium have not been reported much.

3. WORK MATERIAL CONSIDERATIONS

An important area of concern with respect to the role of cutting fluid is the work materials under a given machining environment from tribology point of view. The cutting fluid to be used must facilitate the machining processes involved so as to ensure its compatibility with a wide variety of materials. From tribology point of view various research studies have been carried out [27-30]. In case of materials like cast iron, the brittle behaviour during machining often leads to its breaking and formation of small chips. The influence of friction between cutting tool and the chip is less on account of the small size chip formation. The use of emulsion based cutting fluids enhances some machining characteristics like surface finish quality and, also restricts the formation / coagulation of foreign matter during the machining operations [28,30]. Sulphur added oils are used in the machining of stainless steel materials, which lead to stains over the machined surface [28,30-31]. Water based cutting fluids are used in machining of heat resistant and difficult-to-cut steel alloys, due to the involvement of higher temperature in cutting zone area. However, sulphur based mineral cutting oils may also be used in some machining operations [28,32]. Easy to machine materials like aluminium and aluminium based alloys when subjected to machining, no major issues on account of temperature are encountered. The use of waterless cutting fluids, prevent the formation of built up edge [28,32]. In the machining of copper and copper based alloys, the emulsion based cutting fluids or thin mineral oils are preferred, however for machining of brass, high pressure additive cutting oils are used [28,32].

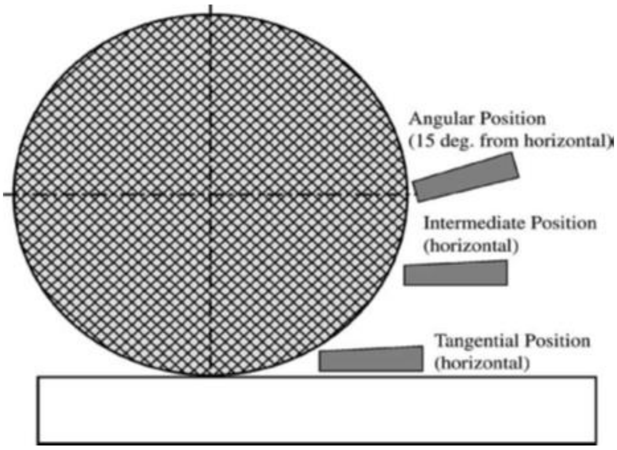

Fig. 1. Nozzle positions [20].

For the machining of difficult-to-cut materials such as titanium alloys, generation of high temperature, is a matter of concern while carrying out the selection of a cutting fluid. The selected cutting fluid must have both cooling and lubricating characteristics. It has been observed that lubrication properties of selected cutting fluids are preferred when low cutting speeds are selected. For composite materials, the cutting fluids influence the surface roughness quality [33].

Patrick et al. [34] studied the effect of cutting fluids on the mechanical properties of mild steel in a turning operation. In this study, the authors have used soluble oil, water and palm kernel oil as cutting fluid for turning operation using Tungsten carbide and HSS as cutting tools. In this study, the researchers have reported that palm kernel oil as a cutting fluid exhibits very good qualities including good chip formation, reduced heat generation and comparatively good surface finish.

Hamdan et al. [35] carried out the performance evaluation of different types of cutting fluid in the machining of AISI 01 hardened steel using pulsating jet minimum quantity lubrication system. In this study, research was carried out using three cutting fluids namely neat oil, soluble oil and semi-synthetic cutting fluids under minimal quantity lubrication (MQL) system with the application of high velocity cutting fluid in narrow pulsed jet forms. The results clearly proved that soluble oil gave the lowest cutting forces and does not change with variable velocities.

Tsao [36] carried out an experimental investigation on cutting fluid effect in milling an aluminum alloy. The experiment shows that adding sulfurous boric acid ester cutting fluid reduced tool wear by 12.5 % for hard coating tungsten carbide end mills and also decreases the milling force by 10 %. Saravanakumar [37] performed an experimental analysis on cutting fluid dispersed with silver nano particles. The research focuses on the performance of the cutting fluid after inclusion of suitable additive, in the form of silver nano particles, in the cutting fluid to improve its thermal and tribological properties. The results have shown a considerable reduction in tool tip temperature, a 8.8 % reduction in cutting forces for the cutting forces with the inclusion of nano particles and 7.5 % improvement in surface roughness. Hung et al. [31] experimentally analyzed the effect of cutting fluid on the machinability of metal matrix composites. The effect of cutting fluid on the machinability of aluminium-based matrix composites reinforced with SiC or Al_2O_3 particles was investigated. The researchers have concluded that pressurized and copious cutting fluid has no effect on tool life due to effective chip flushing and lack of lubricating film.

4. TOOL MATERIAL CONSIDERATIONS

In a machining operation like grinding, the commonly used grinding materials are abrasives. However, on account of the heat generated during the grinding operation and the presence of forces, the use of cutting fluid from tribology point of view is very significant as it may affect the life of the abrasives used and the surface finish characteristics. A wide variety of materials are available for carrying out the machining processes, including the grinding operation [39,40]. However, it becomes necessary to choose a particular cutting fluid-tool material combination so as to get an optimized machining parameters. For materials like tungsten carbide, waterless cutting fluids are preferred [41]. It is important to consider that in case of cutting tool materials, the cutting fluids have a significant role to play. The generation of high heat in the interface of cutting tool (grinding tool) and workpiece material, causes wear of the tool at a much higher rate lowering the tool life and further leading to poor surface quality [28,29]. Some typical grinding materials like cubic boron nitrate (CBN) and polycrystalline diamonds (PCD) may also be used for machining operations [42]. The economic constraints and the high temperature associated with these materials restrict their use. However, such materials are generally used in finishing operations to achieve high dimensional accuracy and surface finish characteristics [28,29].

However, with a particular reference to grinding process, some researchers have suggested rankings of cutting fluids based upon their various properties. Webstar et al. [43] have carried out a study of four cutting fluid types as used in a grinding process as shown in Table 1. In this research study, the researchers have highlighted the characteristics of these fluids. The work carried by Bardie was a further extension to the studies done by Gr et al. [44]. It was observed that no such fluid can be suggested which may act as an ideal alternative. It was further suggested that the parameters such as heat removal, filterability, cost and environmental aspects may be considered altogether. Breingsmeir et al. [45] showed that with the increase in oil additive concentration, there is a decrease in the grinding energy and temperature, however the wheel life increases, later on established and confirmed by Yoon and Krueger [46]. These researchers have observed that diluted synthetic fluids had a grinding ratio (G-ratio) of 2.5 and 7.5, semi-synthetics had G-ratios between 2.5 and 6.5, and soluble oils had G-ratios between 4 and 12. Undiluted cutting fluids had G-ratios between 60 and 120. Minke [47] carried out a research study on the role of coolants in a grinding process. In this research study, the researcher has compared oil and water based cutting fluids under different grinding environments. It was observed during this research work that water-based emulsions have better cooling. However, it leads to generation of higher grinding forces and is not able to prevent damage to the workpiece.

Table 1. Grinding fluid characteristics by Webstar et al. [31].

Characteristics	Synthetics	Semi-synthetics	Soluble oil	Straight oil
Heat removal	4	3	2	1
Lubricity	1	2	3	4
Maintenance	3	2	1	4
Filterability	4	3	2	1
Environmental	4	3	2	1
Cost	4	3	2	1

Ranking Scale: 1-4 where,
1-Worst , 2 –Good , 3- Very Good, 4- Best

Silva et al. [48] carried out an experimental investigation on thermal and rheological behavior of eco-friendly metal cutting fluids The research evaluated the thermal and rheological performance of two chemically modified cottonseed oils epoxidized fluid and hydroxylated fluid, against unmodified cottonseed oil and commercial cutting oils. The results clearly depict that hydroxylated and epoxidized fluids offer better thermal resistance than commercial cutting fluid without causing char formation, and former two fluids are more efficient in lubricating and cooling the drill bit and part, thus causing less wear. Another research study carried out by Ozcelik et al. [49] investigated the effects of vegetable-based cutting fluids on the wear in drilling to investigate the performances of three VBCFs developed from crude sunflower oil, refined sunflower oil, refined canola oil and commercial semi-synthetic cutting fluid and compared the tool wear, thrust force and surface roughness in drilling operation of austenitic stainless steel with HSSE tool. The researchers reported that CCF (canola based cutting fluid)-II is the best cutting fluid for drilling of AISI 304 stainless and gives the best performance due to its higher lubricant properties. Mayr et al. [50] performed an experimental investigation to observe the influence of cutting fluid on thermal behavior of 5-axis machine tools in precision machining. The generated graphs illustrate that measured temperatures are higher without using cutting fluid and cutting fluids can also reduce the chances of errors of the machine tool.

5. HEALTH FACTORS ASSOCIATED WITH CUTTING FLUIDS

The human interaction with the cutting fluids in a conventional machining process has forced the researchers to carry out studies on the health hazards involved in the use of cutting fluids. It has been observed that some of the cutting fluids have proved hazardous to the machine operators [51,52]. The use of cutting fluids in machining processes may often lead to skin related issues. Some typical cases of skin disorders like dermatitis are the most common diseases caused due to frequent exposure to the cutting fluids [53]. There are reports indicating respiratory problems faced by the operators who work continuously in environments where cutting fluids are used. Dahmen et al. [54] carried out a research investigation for separation of debris in a grinding process. In this research study, the researchers have developed a process using supercritical carbon dioxide to separate the debris and it was originally implemented for glass grinding with high oil and lead content.

6. NON TRADITIONAL CUTTING FLUIDS IN A MACHINING PROCESS

Various research studies have been carried out where solid lubricants have been used as a cutting fluid in a machining process. Callister [55] in his research study observed that graphite can be used as a solid lubricant for cutting fluid applications because it possesses weakly bonded hexagonal plate structure. The author also confirmed the use of molybdenum disulfide (MoS2) as a new solid lubricant.

Ninomiya et al. [56] studied the effect of the floating nozzle in grinding of mild steels with vitrified CBN wheel. During his research study the author found that by using a floating nozzle on a CBN wheel, the wheel wear was reduced by 50 % for shallow depths of cut and low workpiece speeds (Fig. 2). The surface finish also improved under these conditions. When compared with traditional coolant application, the author observed that floating nozzle improves the grinding performance with an impressive one twelfth of the cutting fluid, however when the work speeds were increased beyond 20 m/min, there was major wheel wear.

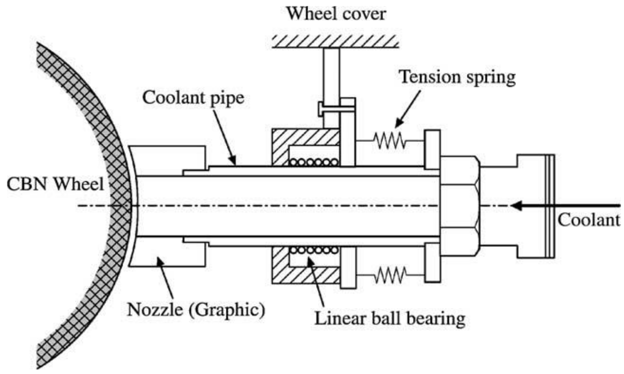

Fig. 2. Schematic diagram of a floating nozzle [36].

Okuyama et al. [57] carried out an experimental investigation of cooling action of grinding fluid in shallow grinding. During this investigation, the authors observed a better performance in grinding by having 4–36 small grooves, 3 mm wide and 0.5 mm deep, attributed to the rise in heat transfer coefficient. A reason for the elevation in the heat transfer coefficient may be due to coolant being held and stirred by the grooves. The researchers suggest that the grooves have a capability of improving the efficiency in heavy grinding with super-abrasive wheels with no porosity as the increased number of grooves also increases the heat transfer coefficient.

Yui and Terashima [58] carried out a research study for development of a coolant-less grinding system. The authors mixed cold air (-30 °C) and vegetable oilmist (0–8.6 cc/h) in order to improve upon cold air application and concluded that the grinding ratio is higher as compared to the traditional grinding method with coolant oil. The investigation revealed that that the critical depth of cut was only 6 mm. Baheti et al. [59] carried out a research study on environmentally conscious cooling and lubrication for grinding. In this research study the authors reported better results upon using environmentally safe ester oil and air during the straight surface grinding of carbon steels using alumunium oxide wheels. A mathematical model of the process was also developed to predict with reasonable accuracy the temperature rise. S.C. Salmon [60] carried out a research study on the effects of hard lubricant coatings on the performance of electro-plated super abrasive grinding wheels. In this research study, the author has used MoS2 as a hard lubricant and titanium aluminum nitride (TiAlN) to resist wear on CBN wheels. During this research study, the author observed that the coated wheels do not require added lubricity of the oil and the CBN wheels operate satisfactorily because they perform adequately with water-based fluids. The author also observed that coated wheels perform better than the traditional wheels, due to their compatibility with the environmentally-friendly water-based coolants.

Choi et al. [61] carried out a comparison of the cooling effects of compressed cold air and coolant for cylindrical grinding with a CBN wheel. The authors reported that the effectiveness of cold air was nearly comparable with conventional wet-grinding for shallow depths of cut; however, the surface roughness would increase as the tensile surface residual stresses would appear upon increasing the depths of cut as a result of the lack of lubrication through the grinding zone. Inoue and Aoyama [62] carried out an experimental investigation on application of air cooling technology and minimum quantity lubrication to relief grinding of cutting tools. The authors used cold air at -33 °C with a cooling air output flow of 320 Nl/min at a pressure of 200 kPa. The lubricant was 'salad oil' and was supplied at 6 m/min. The results from this setup were compared with dry grinding and grinding with an oil-based fluid. During this experimental investigation, the authors concluded that when the depth of cut exceeded 0.1 mm, the oil-based cutting-fluid grinding exhibited the lowest temperature rise. It was observed that conventional oil-based cutting-fluid grinding has an advantage over cooling-air and minimum-quantity lubricant application in terms of temperature rise control for large depths of cut.

Xu et al. carried [63-67] out a research on heat transfer characteristics in grinding contact zone with radial water jet impinging cooling. The authors worked with a radial cooling mechanism. It was found that by using perforated electroplated CBN grinding wheels with radial jets, where the fluid is forced from the cooling holes at high pressure, the fluid tends to break the boundary layer. The authors were able to improve the critical heat flux and the cooling effect in the contact zone which increased overall efficiency. The temperature of the workpiece surface in the grinding zone was steadily kept below the film boiling temperature of 100–120 °C for water based coolants, even with a high heat flux. Shaji and Radhakrishnan [68] carried out an experimental investigation on surface grinding using graphite as a lubricant. The authors used graphite paste with water-soluble oil as a lubricant in a grinding process and compared the performance of graphite-assisted grinding with dry grinding and conventional wet grinding by varying the workpiece material, dressing conditions and cutting fluid application. In this research study the authors observed that the tangential forces, grinding zone temperatures and specific energies are lower with the graphite paste when compared to dry or coolant grinding but the system has problems with wheel clogging and grinding ductile materials. Yokogawa et al. [69] carried out a research work on improving grinding performance of BN wheels by dual-fluid supply method. During this research study, the authors used a dual cutting fluid method in a cylindrical grinding operation using mineral oil as a lubricant in the grinding zone and used water to cool the workpiece. The experiments were carried out with a removal rate of 1200 mm^2/min, a wheel speed of 3600 m/min, and a CBN wheel. Coolant water was applied to the underside of the workpiece via a positional nozzle, (Fig. 3). The results showed that surface roughness of the workpiece dramatically improved. With conventional cutting fluid applications the surface roughness was approximately 3 mm R_z but with the dual cutting fluid application the surface roughness dropped to under 1 mm R_z for the same removal.

Shaji and Radhakrishnan [70] carried out another experimental investigation on the application of solid lubricants in grinding on graphite sandwiched grinding wheels. Slotted wheels were used with graphite impregnated into the slots. Three different wheels with varying numbers of slots: 10, 15 and 20 were used. Compared to conventional dry- and wet-grinding, the normal forces with the graphite slotted wheels came out to be more or less the same or even slightly higher at low feed rates, but at increased feed rates, these forces were higher in most cases. The results showed that the surface roughness, residual stresses and hardness profiles were greatly improved with the graphite wheels. These experiments were performed with small depths of cut and do not represent a considerable improvement over more traditional cutting fluid application. Shetty et al. [71] carried out tribological investigation of discontinuously reinforced aluminium composites based on the orthogonal arrays.

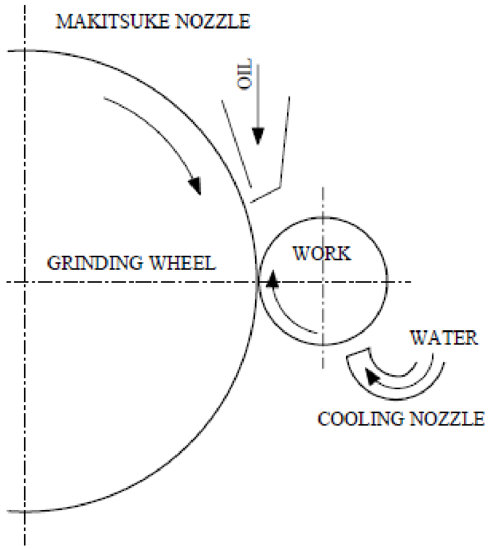

Fig. 3. Dual cutting fluid setup [49].

In this tribological investigation, the tests were carried out under dry, oil and water based emulsion and steam lubricated (cutting fluid) conditions. Both The tool wear and surface roughness were found to be less for steam cutting in this investigation.

Anjaiah et al. [72] used a pressurized steam jet approach to tool wear minimization in cutting of metal matrix composites by full factorial design of experiments. In this experimental analysis, the researchers have observed that pressurized steam jet plays a significant role on the tool wear. Kuram et al. [73] carried out a research study on the optimization of the cutting fluids and parameters using taguchi and ANOVA in milling. In this research study, the researchers have considered two different vegetable based cutting fluids developed from refined canola and sunflower oil and a commercial type semi-synthetic cutting fluid. The optimum conditions for tool wear and forces were studied. Walter Belluco and Leonardo De Chiffere [74] carried out a research study on testing of vegetable based cutting fluids by hole making operations, using vegetable oil as cutting fluid for drilling operations, involved drilling, tapping and reaming operations and results indicated that while reaming, higher cutting speeds had a strong impact on part accuracy and at smaller cutting speeds, the effect considerably reduced.

7. MINIMUM QUANTITY LUBRICATION AND TRIBOLOGY

During the past few years, a new trend in the use of cutting fluids technology in a machining environment is MQL (minimum quantity lubrication). MQL is being adopted nowadays for high speed machining operations. This type of advanced lubrication systems in a machining environment plays a vital role particularly in large cutting fluids application and dry machining. Minimum quantity lubrication (MQL) also known as Near Dry Machining (NDM) or semi dry machining is an alternative to traditional use of cutting fluids. In MQL, there is a use of very small quantity of lubricant for lubrication or cooling requirements. Minimum quantity lubricants (MQL) systems generally consists of cutting fluids (coolants and lubricants) which are non-soluble in water. These fluids however, reduce the health hazards associated which may affect the health of the machinist [75]. Some research studies have revealed that use of MQL technique enhances lubrication and also leads to minimum power consumption in a grinding process (grinding power). The wear rate of the grinding wheel also reduces in a significant way [76].

Tawakoli et al. [77] investigated the the performance of MQL technique in a grinding operation. In this investigation, the researchers have considered both hard steel 100cr6 and soft steel 42CrMo4 for investigation. It was observed that for LB8000 MQL oil with wheel speed 25 m/s and depth of cut 25μm the improvement in surface quality in MQL grinding is more significant in comparison to dry and fluid grinding. Dhar et al. [78] investigated the effect of MQL technique to grind 16MnCr5 alloy steel on the cutting performance compared to completely dry cutting and flood cooling with respect to grinding temperature, surface roughness, chip morphology. The results indicate that the use of minimum quantity lubrication (MQL) by cutting oil (VG-68) leads to lower surface roughness compared to dry and wet environments. Silva et al. [79] investigated the performance of MQL system to grind ABNT 4340 steel (HRC 60) with alumina wheel. It was found that, MQL system leads to finer surface finish and higher compressive residual stress compared to dry and conventional cooling. Sabahudin et al. [80] in his research study broadly discussed the application of marginal amount of coolant instead of large coolant fluid used in machining, known as Minimum Quantity Lubrication (MQL) machining. The study revealed that the MQL machining leads to lesser cutting forces, less strain hardening and a favourable chip formation process.

8. FUTURE SCOPE

The literature revealed the below mentioned gaps in the research work performed till date and the future work should be focussed in the following areas so as to lead to the further developments in this area of research:

1. Development of biocompatible cutting fluids with minimum or no toxic harm rate.
2. Recycling / reclamation of cutting fluids.
3. Development of cutting fluids for high temperature tribological applications.
4. A system of studying the wetability characteristics with addition of nanoparticles.
5. Development of new cooling techniques in dry machining.
6. Development of some more nano-cutting fluids aimed at reducing the cutting forces and increasing the tool life with minimum energy consumption at reduced costs.

9. CONCLUSIONS

The cutting fluids used in a grinding process significantly improve the machining characteristics of the process. Grinding process is one of the important machining operations in a manufacturing environment. Apart from cooling the cutting fluids also perform the lubrication at the tool-workpiece interface. Recent developments in the cutting fluid technology have led to rapid changes in the design and development of various cutting fluids, used for various grinding operations. The concepts like minimum quantity lubrication (MQL) in grinding operations have greatly influenced the material removal rate (MRR) and also the life of cutting tool. Some of the key areas which have been considered in this research article are:

- Cutting Fluids and its types
- Health hazards with cutting fluids
- Work material considerations with cutting fluids
- Tool material considerations
- Minimum quantity lubrication in grinding systems

REFERENCES:

[1] A.P. Viktor, ‘Tribology of metal cutting’, *Mechanical Tribology, New York: Marcel Dekker,* pp 307-346, 2004.

[2] G. Wit, J. Rech and K. Żak, ‘Determination of friction in metal cutting with tool wear and flank face effects’, *Wear*, vol. 317, no. 1, pp. 8-16, 2014.

[3] M. Fallqvist, F. Schultheiss, R. Msaoubi, M. Olsson and J.-E. Stahl, ‘Influence of the tool surface micro topography on the tribological characteristics in metal cutting: Part I experimental observations of contact conditions’, *Wear,* vol. 298, pp. 87-98, 2013.

[4] U. Durul and T. Özel. ‘Determination of tool friction in presence of flank wear and stress distribution based validation using finite element simulations in machining of titanium and nickel based alloys’, *Journal of Materials Processing Technology,* vol. 213, no. 12, pp. 2217-2237, 2013.

[5] P. Hendrik, F. Klocke and D. Lung, ‘A new experimental methodology to analyse the friction behaviour at the tool-chip interface in metal cutting’, *Production Engineering,* vol. 6, no. 4-5, pp. 349-354, 2012.

[6] Y.M. Shashidhara and S.R. Jayaram, ‘Vegetable oils as a potential cutting fluid—an evolution’, *Tribology International*, vol. 43.5, pp 1073-1081, 2010.

[7] S.M. Alves and J.F. Oliveira, ‘Development of new cutting fluid for grinding process adjusting mechanical performance and environmental impact’, *Journal of Materials Processing Technology*, vol. 179, no. 2, pp. 185-189, 2006.

[8] H.S. Abdalla, W. Baines, G. Mclntyre and C. Slade, ‘Development of novel sustainable neat-oil metal working fluids for stainless steel and titanium alloy machining, Part 1. Formulation development’, *The International Journal of Advanced Manufacturing Technology*, vol. 34, no. 1-2, pp. 21-33, 2007.

[9] L. Sunday Albert, ‘A review of application of vegetable oil-based cutting fluids in machining non-ferrous metals’, *Indian Journal of Science and Technology,* vol. 6, no. 1, pp. 3951-3956, 2013.

[10] E. Kuram, B. Ozcelik and E. Demirbas, ‘Environmentally friendly machining: vegetable based cutting fluids’, *Green Manufacturing Processes and Systems*, *Springer, Berlin, Heidelberg*, pp. 23-47, 2013.

[11] J.S McCoy, *Introduction: Tracing the historical development of metalworking fluids*. In: JP Byers, Ed. Metalworking Fluids, New York: Marcel Dekker, pp. 1-23, 1994.

[12] A.R Machado and J. Wallbank, ‘The effect of extremely low lubricant volumes in machining’, *Wear*, vol. 210, pp. 76-82, 1997.

[13] R.C Gunderson and A.W Hard, *Synthetic Lubricants*, Reinhold, New York, 1962.

[14] J.A. Schey, ‘*Metal Deformation Processes: Friction and Lubrication*, Marcel Dekker Inc, New York, 1970.

[15] P.S. Sreejith and B.K.A. Ngoi, ‘*Dry machining: machining of the future*’, Journal of Materials Processing Technology, vol. 101, pp. 287-291, 2000.

[16] L.D. Chiffre, ‘Function of cutting fluids in machining’, *Lubrication Engineering*, vol. 44, pp. 514-518, 1988.

[17] V.P. Astakhov, *Tribology of metal cutting*, Mechanical Tribology, New York: Marcel Dekker, pp. 307-346, 2004.

[18] B.L. Juneja, *Fundamentals of metal cutting and machine tools*, New Age International, 2003.

[19] E.M. Trent and P.K. Wright, *Metal cutting*. Butterworth-Heinemann, 2000.

[20] N.R. Dhar and M. Kamruzzaman, ‘Cutting temperature, tool wear, surface roughness and dimensional deviation in turning AISI-4037 steel under cryogenic condition’, *International Journal of Machine Tools and Manufacture*, vol. 47, no. 5, pp. 754-759, 2007.

[21] S.Y. Hong, Y. Ding and R.G. Ekkens, ‘Improving low carbon steel chip breakability by cryogenic cooling’, *International Journal of Machine Tools and Manufacture*, vol. 39, pp. 1065-1085, 1999.

[22] Z.Y. Wang and K.P. Rajurkar, ‘Cryogenic machining of hard-to-cut materials’, *Wear*, vol. 238, pp. 169-175, 2000.

[23] M. Stanford, P.M. Lister, C. Morgan and K.A. Kibble, ‘Investigation into the use of gaseous and liquid nitrogen as a cutting fluid when turning BS 970-80A15 (En32b) plain carbon steel using WC–Co uncoated tooling’, *Journal of Materials Processing Technology*, vol. 209, no. 2, pp. 961-972, 2009.

[24] C. Machai and D. Biermann, ‘Machining of β-titanium-alloy Ti–10V–2Fe–3Al under cryogenic conditions: Cooling with carbon dioxide snow’, *Journal of Materials Processing Technology*, vol. 211, no. 6, pp. 1175-1183, 2011.

[25] S. Hesterberg, ‘Dry machining of stainless steels: process design for turning and drilling with indexable inserts’, *Vulkan-Verlag GmbH*, vol. 35, 2006.

[26] B.D. Jerold and M.P. Kumar, ‘Experimental comparison of carbon-dioxide and liquid nitrogen cryogenic coolants in turning of AISI 1045 steel’, *Cryogenics*, vol. 52, no. 10, pp. 569-574, 2012.

[27] M.A. El Baradie, ‘Cutting Fluids, Part I: Characterisation’, *Journal of Materials Processing Technology*, vol. 56, pp. 786-797, 1996.

[28] G. Avuncan, *Machining Economy and Cutting tools*, Makine Takim Endüstrisi Ltd. Publication, Istanbul (in Turkish), pp. 375-403, 1998.

[29] Kavuncu, *Cutting Oils In Metal Machining, Turkish,* Chambers of Mechanical Engineers Publication, Istanbul (in Turkish).

[30] ASM Committee, *Machining of titanium alloys*, *Metals Handbook*, ASM Publication, 499-507.

[31] E.O. Ezugwu, J. Bonney and Y. Yamane, ‘An overview of the machinability of aerospace alloys’, *Journal of Materials Processing Technology*, vol. 134, pp. 233-253, 2003.

[32] S. Ebbrell, N.H. Woolley, Y.D. Trimidas, D.R. Allanson and W.B. Rowe, ‘The effects of cutting fluid application methods on the grinding process’, *International Journal of Machine Tools and Manufacture,* vol. 40, pp. 209-223, 2000.

[33] N.P. Hung, S.H. Yeo and B.E. Oon, ‘Effect of cutting fluid on the machinability of metal matrix composites’, *Journal of Materials Processing Technology*, vol. 67, pp. 157-161, 1997.

[34] P.A.O. Adegbuyi, G. Lawal, O. Oluseye and G. Odunaiya, ‘Analysing the effect of cutting fluids on the mechanical properties of mild steel in a turning operation’, *American Journal of Scientific and Industrial Research,* vol. 2, no. 1, pp. 1-10, 2011.

[35] A. Hamdan and M. Fadzil, K.A. Abou-El-Hossein and M. Hamdil, ‘Performance evaluation of different types of cutting fluid in the machining of AISI 01 hardened steel using pulsed jet minimal quantity lubrication system’, pp. 1-9, *Invited Paper.*

[36] C.C. Tsao, ‘An experiment study of hard coating and cutting fluid effect in milling aluminum alloy’, *International Journal of Advanced Manufacturing Technology*, vol. 32, pp. 885–891, 2007.

[37] N. Saravanakumar, L. Prabu, M. Karthik and A. Rajamanickam, ‘Experimental analysis on cutting fluid dispersed with silver nano particles’, *Journal of Mechanical Science and Technology*, vol. 28, no. 2, pp. 645-651, 2014.

[38] N.P. Hung, S.H. Yeo, B.E. Oon, ‘Effect of cutting fluid on the machinibility of metal matrix composites’, *Journal of Material Processing Technology*, vol. 67, pp. 157-161, 1997.

[39] M.A. Shalaby, M.A. El Hakim, M.M. Abdelhameed, J.E. Krzanowski, S.C. Veldhuis and G.K. Dosbaeva, ‘Wear mechanisms of several cutting tool materials in hard turning of high carbon–chromium tool steel’, *Tribology International,* vol. 70, pp.148-154, 2014.

[40] T. Doi, E. Uhlmann and I.D. Marinescu eds., *Handbook of Ceramics Grinding and Polishing*. William Andrew, 2015.

[41] O. Çakīr, A. Yardimeden, T. Ozben and E. Kilickap, ‘Selection of cutting fluids in machining processes’, Journal of Achievements in materials and Manufacturing engineering, vol. 25, no. 2, pp. 99-102, 2007.

[42] F. Nabhani, ‘Wear mechanisms of ultra-hard cutting tools materials’, *Journal of Materials Processing Technology*, vol. 115, no. 3, pp. 402-412, 2001.

[43] J.A. Webster, C. Cui and R.B. Mindek Jr., ‘Grinding fluid application system design’, *CIRP Annals*, vol. 44, no. 1, pp. 333–338, 1995.

[44] P.Q. Ge, L. Wang, Z.Y. Luan and Z.C Liu, ‘Study on service performance evaluation of grinding coolants’, *Key Engineering Materials*, vol. 258–259, pp. 221–224, 2004.

[45] E. Brinksmeir, C. Heinzel and M. Wittman, ‘Friction, cooling and lubrication in grinding’, *Annals of the CIRP*, vol. 48, no. 2, pp. 581–598, 1999.

[46] S.C. Yoon and M. Krueger, ‘Optimizing grinding performance by the use of sol–gel alumina abrasive wheels and a new type of aqueous metalworking fluid’, *Machining Science and Technology*, vol. 3, no. 2, pp. 287–294, 1999.

[47] E. Minke, ‘Contribution to the role of coolants on grinding process and work results Technical Paper’, *Society of Manufacturing Engineers*, MR (MR99-227), pp. 1–18, 1999.

[48] F. Silva Viviane, N. Batista Luciano, 'Robertis Eveline De, Castro Claudia S. C., Cunha Valnei S., Costa Marcos A. S., ‘*Thermal and rheological behavior of ecofriendly metal cutting fluids’, J Therm Anal Calorim*, DOI 10.1007/s10973-015-4848-X.

[49] B. Ozcelik, E. Kuram, E. Dmeribas and S. Emrah, ‘Effects of vegetable-based cutting fluids on the wear in drilling’, *Sadhana*, *Indian Academy of Sciences*, vol. 38, no. 4, pp. 687–706, 2013.

[50] M. Josef, G. Michael, M.B. Benjamin, S. Weikert and W. Konrad, ‘Cutting fluid influence on thermal behavior of 5-axis machine tools’, in *6th CIRP International Conference on High Performance Cutting*, 2014.

[51] M.L. Hoff, ‘Cutting fluids: necessary nuisance to productivity tool’, *Society of Manufacturing Engineers*, MR (MR02-302), pp. 1–6, 2002.

[52] C.A. Sluhan, ‘Selecting the right cutting and grinding fluids’, *Tooling and Production*, vol. 60, no. 2, pp. 1-7, 1994.

[53] H.S.E. Anon, ‘Warnings for grinding coolants”, *Metalworking Production’*, vol. 147, no. 5, 2003.

[54] N. Dahmen, J. Schon, H. Schmieder and K. Ebert, ‘Supercritical Fluid Extraction of Grinding and Metal Cutting Waste Contaminated with Oils’, *ACS Symposium Series,* vol. 670, pp. 270–279, 1997.

[55] W.D. Callister Jr., *Materials Science and Engineering an Introduction*, Fifth ed., Wiley, New York, 2000.

[56] S. Ninomiya, M. Iwai, T. Uematsu, K. Suzuki and R. Mukai, ‘Effect of the floating nozzle in grinding of mild steels with vitrified CBN wheel’, *Key Engineering Materials*, vol. 257–258, pp. 315–320, 2004.

[57] S. Okuyama, Y. Nakamura and S. Kawamura, ‘Cooling action of grinding fluid in shallow grinding’, *International Journal of Machine Tools and Manufacture*, vol. 33, no. 1, pp. 13–23, 1999.

[58] A. Yui and M. Terashima, *Proceedings of the Third International Conference on Abrasive Technology*, pp. 394, 1999.

[59] U. Baheti, C. Gou and S. Malkin, ‘Environmentally Conscious Cooling and Lubrication for Grinding’, *Proceedings of the International Seminar on Improving Machine Tool Performance*, San Sebastian, Spain, vol. 2, pp. 643–654, 6–8 July, 1998.

[60] S.C. Salmon, ‘The effects of hard lubricant coatings on the performance of electro-plated superabrasive grinding wheels’, *Key Engineering Materials*, vol. 238–239, pp. 283–288, 2003.

[61] H.Z. Choi, S.W. Lee and H.D. Jeong, 'A comparison of the cooling effects of compressed cold air and coolant for cylindrical grinding with a CBN wheel', *Journal of Materials Processing Technology*, vol. 111, pp. 265–268, 2001.

[62] S. Inoue and T. Aoyama, 'Application of air cooling technology and minimum quantity lubrication to relief grinding of cutting tools', *Key Engineering Materials*, vol. 257–258, pp. 345–350, 2004.

[63] H.J. Xu, Y.C. Fu and F.H. Sun, 'Research on enhancing heat transfer in grinding contact zone with radial water jet impinging cooling', *Key Engineering Materials*, vol. 202–203, pp. 53–56, 2001.

[64] L. Zhen-Chang, A. Satoshi and N. Masahiro, 'Influence of grinding oil viscosity on grinding heat and burn damage in creep-feed grinding', *Lubrication Engineering,* vol. 51, no. 8, pp. 647–651, 1995.

[65] W. Graham and M.G. Whiston, 'Some observations of through-wheel application in grinding', *International Journal of Machine Tool Design and Research*, vol. 18, pp. 9–18, 1978.

[66] T. Suto, T. Waida, H. Noguchi and H. Inoue, 'High performance creep feed grinding of difficult to machine materials with new-type wheels', *Japan Society of Precision Engineering*, vol. 24, no. 1, pp. 39–44, 1990.

[67] S.M. Rezaei, T. Suto, T. Waida and H. Noguchi, 'Creep feed grinding of advanced ceramics, Proceedings of the Institution of Mechanical Engineers', *Part B: Journal of Engineering Manufacture*, vol. 206, B2, pp. 93–99, 1992.

[68] S. Shaji and V. Radhakrishnan, 'An Investigation on surface grinding using graphite as lubricant', *International Journal of Machine Tools and Manufacture*, vol. 42, pp. 733–740, 2001.

[69] M. Yokogawa and K. Yokogawa, 'Improving grinding performance of CBN wheels by dual-fluid supply method', *International Journal of the Japan Society for Precision Engineering*, vol. 27, no. 1, 1993.

[70] S. Shaji and V. Radhakrishnan, 'Application of solid lubricants in grinding: investigations on graphite sandwiched grinding wheels', *Machining Science and Technology*, vol. 7, no. 1, pp. 137–155, 2003.

[71] R. Shetty, R.B. Pai, S.S. Rao, 'Tribological studies on discontinuously reinforced aluminium composites based on the orthogonal arrays', *ARPN Journal of Engineering and Applied Sciences*, vol. 3, no. 1, pp. 94-92, 2008.

[72] D. Anjaiah, R. Shetty, R.B. Pai, M.V. Kini and S.S. Rao, *'A pressured steam jet approach to tool wear minimization in cutting of metal matrix composites', Materials Science Forum*, vol. 561-565, pp. 643-646, 2007.

[73] E. Kuram, B.T. Simsek, B. Ozcelik, E. Demirbas and S. Askin, 'Optimization of the Cutting Fluids and Parameters Using Taguchi and ANOVA in Milling', *Proceedings of the World Congress on Engineering,* Vol II, London, U.K., 2010,

[74] W. Belluco and L. De Chiffrie, 'Testing of vegetable based cutting fluids by hole making operations', *Society of Triblogists and Lubrication Engineers at ASME Tribological Conference*, Janauary 2001.

[75] U. Heisel, D. Lutz, R. Wassmer and U. Walter, 'The Minimum Quantity Lubricant Technique and its Application in the Cutting Process', *Machines and Metals Magazine*, vol. 386, pp. 22-38, 1998.

[76] D. Hafenbraedl and S. Malkin, 'Technology Environmentally Correct for Intern Cylindrical Grinding', *Machines and Metals Magazine*, vol. 426, pp. 40-55, 2001.

[77] T. Tawakoli, M.J. Hadad, M.H. Sadeghi, A. Danesh, S. Stockert and A. Rasifard, 'An experimental investigation of the effects of workpiece and grinding parameters on minimum quantity lubrication—MQL grinding', *International Journal of Machine Tools & Manufacture*, vol. 49, pp. 924–932, 2009.

[78] N.R. Dhar, M. Hossain and M. Kamruzzaman, 'MQL applications in grinding of 16mncr5 steel: A comparison with wet and dry grinding', *Proceedings of the International Conference on Mechanical Engineering*, Dhaka, Bangladesh, ICME 05-AM-33, 2005.

[79] L.R. Silva, E.C. Bianchi, R.E. Catai, R.Y. Fusse, T.V. Franc and P.R. Aguiar, 'Analysis of surface integrity for minimum quantity lubricant-MQL in grinding', *International Journal of Machine Tools and Manufacture*, vol. 47, pp. 412–418, 2007.

[80] S. Ekinovic, E. Begovic, E. Ekinovic and B. Fakic, 'Cutting forces and chip shape in MQL machining of Aluminium Bronze', *Journal of Trends in the Development of Machinery and Associated Technology*, vol. 17, no. 1, p.p. 17-20, 2013.