Chapter 2
Machining with Minimal Cutting Fluid

Abstract The purpose of cutting fluid in a machining operation is to cool the workpiece, reduce friction, and wash away the chips. The cutting fluid contributes significantly toward machining cost and also possesses environmental threats. In the past, there have been some attempts to minimize the amount of cutting fluid in machining. This chapter reviews some prominent ways to minimize the application of cutting fluid and their impact on the machining performance.

Keywords Cutting fluids • Disposal of cutting fluids • Internal coolant supply • Minimal quantity lubrication • Minimum quantity cooling lubrication • Mist lubrication • Nanofluids • Near dry grinding • Straight cutting oils • Water-mix fluids

2.1 Introduction

Cutting fluids are employed in machining to reduce friction, cool the workpiece, and wash away the chips. With the application of cutting fluid, the tool wear reduces and machined surface quality improves. Often the cutting fluids also protect the machined surface from corrosion. They also minimize the cutting forces thus saving the energy. These advantages of using cutting fluids in machining are accompanied by a number of drawbacks. Sometimes the cutting fluid costs are more than twice the tool-related costs (Astakhov 2008). Most of the cutting fluids possess the health hazard to the operator. Disposal of the used cutting fluid is also a major challenge.

In the recent past, there has been a general liking for dry machining (Sreejith and Ngoi 2000). On the other hand, several researchers started exploring the application of minimal cutting fluid. In this chapter, a review of the application of minimal cutting fluid in machining is presented.

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2.2 Major Concerns in Using Cutting Fluids

There are mainly two types of cutting fluids used in machining (1) neat oils or straight cutting oils (2) water-mix fluids. Neat oils are based on mineral oils and used for the metal cutting without further dilution. They are generally blends of mineral oils and other additives. The most commonly used additives are fatty materials, chlorinated paraffin, sulfurized oils, and free sulfur. Sometimes organic phosphorous compounds are also used as additives. Extreme pressure additives containing chlorine, sulfur, or phosphorous react in the tool–chip interface producing metallic chlorides, phosphates, and sulfides, thus protecting the cutting edge (Trent 1984). Neat oils provide very good lubrication but poor cooling. Water-mix fluids are of three types (a) emulsifiable oils (b) pure synthetic fluids (c) semisynthetic fluids. Emulsifiable oils form an emulsion when mixed with water. They are used in a diluted form with concentration of 3–10%. The concentrate consists of a base mineral oil and emulsifiers. These oils produce good lubrication and cooling. Pure synthetic fluids contain no petroleum or mineral oil base and are formulated from alkaline inorganic and organic compounds with additives for corrosion inhibition. They are used in a diluted form with concentration of 3–10%. They provide very good cooling performance. Semisynthetic fluids are the mixture of emulsifiable oils and pure synthetic fluids. Their characteristics are the mix of the characteristics of emulsifiable and pure synthetic oils.

Cutting fluids often pose hazard to man, machine, and material. For example, a cutting fluid with fatty material reacts with the zinc and produces zinc soap. Hence, the use of galvanized tanks, pipes, and fittings should be avoided with it. Fatty oil based fluids readily oxidize, particularly in the presence of a catalyst like copper. Thus, during the machining of copper, fat is converted to organic acid which reacts with exposed copper surface to produce green color copper soaps. Presence of chlorine also poses health hazard. Sulfur also reacts with many metals to make sulfides.

Water-mix fluids cause staining and corrosion. They also produce microorganisms. All water-mix cutting fluids are alkaline for inhibiting the corrosion. It also helps to control the growth of microorganisms. However, excessive alkalinity causes irritation to human skin. It also causes corrosion problems in aluminum and zinc. As the magnesium is very reactive with water, it should not be machined with water-mix fluid. Synthetic fluids usually contain triethanolamine which reacts with copper. They are also not suitable for machining of aluminum. Hope (1977) has reviewed staining and corrosion tendencies of cutting fluids.

A number of occupational diseases of operators are due to skin contact with cutting fluids. Direct skin contact can cause an allergic reaction or dermatitis. The petroleum products that are basis for the majority of the fluids are suspected carcinogens. It was noted that machinists exhibited a higher rate of upper respiratory tract cancer than other workers. Applying the cutting fluid in the form of oil mist also poses serious health hazards. The contact of mist with eye may cause irritation and the mist may affect adversely to asthma patients. It may also cause long time breathing disorders. According to the Occupational Safety and Health

Administration (OSHA), the permissible exposure level of mist within the plant is 5 mg/m^3, which may be reduced to 0.5 mg/m^3. Another problem with the use of cutting fluids is that in many cases, the harmful effects of the cutting fluids are not known due to lack of studies (Bennett 1983). Some studies have indicated that the respiratory exposure to ozone or nitrogen oxide in combination with exposure to oil mists increases the toxic effects of the oxidants. The toxicity of formaldehyde vapors increases in the presence of nontoxic aerosols (mists) of mineral oils or glycols.

The disposal of cutting fluids is also a big problem. The waste cutting fluids can pollute surface and groundwater. They can cause soil contamination, affect agriculture produce, and can lead to food contamination. Thus, ideally, cutting fluids should not be used at all. If it is not possible, then their use should be minimized. One alternative is to develop completely safe cutting fluids, but they may not be competitive due to economic consideration.

2.3 Minimum Quantity Lubrication Systems

The conventional system of applying the coolant is flood coolant system, in which a large quantity of coolant is continuously impinged on the rake face of the tool. This system is very inefficient. First of all, a large quantity of the cutting fluid is required. Second, the cutting fluid is not able to reach the cutting zone due to obstruction from chips.

A better method is the application of mist lubrication, in which a mixture of air and cutting called aerosol is produced and supplied in the cutting zone with a high pressure. The system uses an atomizer. The atomizer is an ejector where the compressed air is used to atomize the cutting oil (Fig. 2.1). Oil is then conveyed by the air in a low-pressure distribution system to the machining zone. As the compressed air flows through the venturi path, the narrow throat around the discharge nozzle creates a venturi effect in the mixing chamber, i.e., a zone where the static pressure is below the atmospheric pressure (often referred to as a partial vacuum). This partial vacuum draws the oil up from the oil reservoir where the oil is maintained under a constant hydraulic head. The air rushing through the mixing chamber atomizes the oil stream into an aerosol of micron-sized particles. When the aerosol impinges through the jet, it produces a spray of gaseous suspension called mist in the machining zone which works as cooling as well as lubricating medium. However, mist also poses a health hazard.

Instead of applying the cutting fluid from an external nozzle, channels can be made in the tool for supply of cutting fluid to the high temperature zone. Figure 2.2 is a schematic representation of such type of tool, in which the high pressure coolant is forced through a hole to reach the cutting face of the tool. This type of arrangement was used about 2 decades earlier by Wertheim et al. (1992). In their arrangement, the cutting fluid is able to reach the cutting zone more effectively than through external application. In the conventional flood coolant system, the heat

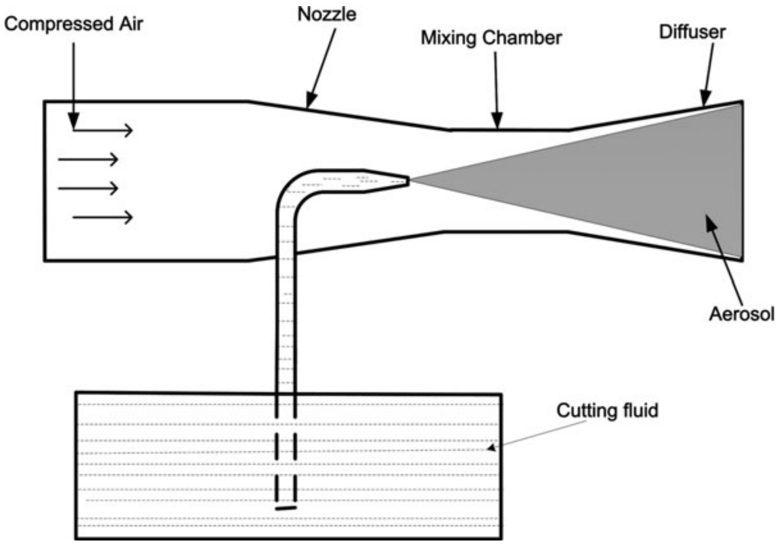

Fig. 2.1 Schematic of an atomizer

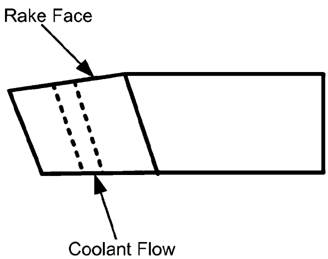

Fig. 2.2 A cutting tool with an internal coolant supply

causes the evaporation of the coolant before it reaches the critical area. Wertheim et al. (1992) used a high pressure system. The pressure was increased up to 25 bar. This system reduced tool wear and improved the tool life. In the grooving in alloy steel by TiC + TiCN + TiN coated carbide tool, it was observed that tool could make 40 grooves when the flushing pressure was 1 bar. With 5-bar pressure, the tool life was 75 grooves and with 25-bar pressure, a total of 160 grooves were produced before the tool failed. Similar phenomenon was observed when grooving a high temperature alloy, Inconel 718. When using a cutting speed of 30 m/min at a feed of 0.16 mm/rev, a tool life of only 3 min was reached with conventional flushing. Using the internal flushing at 16 bar under the same machining conditions, a total tool life of over 14 min was achieved. Compared to conventional system, the requirement of the coolant got drastically reduced. Kovacevic et al. (1995) studied the performance of a face milling process, in which a high pressure water jet was

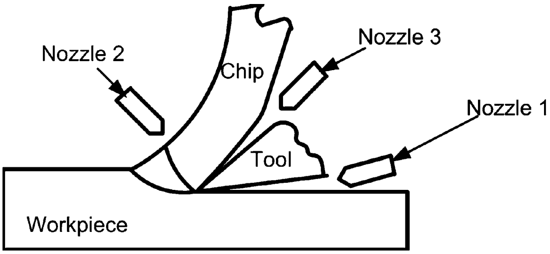

Fig. 2.3 MQL application with three jets

delivered into tool–chip interface through a hole in the tool rake face. Senthil Kumar et al. (2002) applied a high pressure (17 bar) cooling system in high speed milling, in which the cutting fluid was supplied though the spindle.

Weinert et al. (2004) have presented an excellent review of dry machining and minimum quantity lubrication (MQL). When the primary objective is to carry out lubrication, the system is MQL. When both cooling and lubrication are needed, it is called Minimum Quantity Cooling Lubrication (MQCL). In MQCL operations, the media used is generally straight oil, but some applications have used an emulsion or water. The cutting oil can be sent with air in the form of aerosol or without air. In MQL or MQCL system, the normal consumption of cutting fluid medium is 5–50 ml/min. The supply of cutting fluid can be external (through nozzles) or internal (through a channel) in tool. There can be a single channel system or double channel system, in which the air and oil are fed separately.

The fluid used in MQL or MQCL system should be biodegradable and stable. As the consumption of the oil is very less, the fluid should remain stable for a longer period of time. Vegetable oils and synthetic esters have been used as cutting fluids in MQL applications (Khan and Dhar 2006; Wakabayashi et al. 2003). A synthetic ester has a high boiling temperature and flash point and a low viscosity and thus leaves a thin film of oil on the workpiece which serves to resist corrosion. Synthetic esters are biodegradable also.

Method of applying the cutting fluid has a great effect on machining performance in an MQL system. In an orthogonal machining, cutting fluid can be injected at three places through different nozzles as shown in Fig. 2.3. Cutting fluid injected through Nozzle 1 reduces the friction between tool and workpiece and helps in reducing flank wear. The injection of fluid at Nozzle 2 helps in the curling of chips because of Rebinder effect and cooling. Here, some heat from primary shear zone is taken away. The injection through Nozzle 3 helps in taking the heat away from secondary shear zone on the rake face.

Varadarajan et al. (2002) supplied the specially formulated cutting fluid in the form of thin pulsed jet in the hard turning process. A fuel pump of diesel engine was used for injection. The system can deliver cutting fluids through six outlets simultaneously, but the study was conducted with one outlet only. The nozzle position approximately corresponded to Nozzle 1 in Fig. 2.3. The typical rate of discharge was 2 ml/min. The jet velocity is of the order of 100 m/s at a pressure of 200 bar.

The fluid was injected in pulses at a pulse rate of 600 pulses/min. The system provided very good performance in terms of cutting forces, cutting temperature, tool life, surface finish, cutting ratio, and tool–chip contact length.

Attanasio et al. (2006) studied the performance of MQL turning by injecting the lubricants on rake and flank separately. Referring Fig. 2.3, once the lubricant was injected through Nozzle 1 and another time through Nozzle 3. The conclusion was that injecting the lubricant on the flank surface is better.

Ram Kumar et al. (2008) applied minimum cutting fluid through two jets in a hard turning process. One high velocity pulsating jet was applied at the tool–work interface and other was applied on the top surface of the chip as shown (corresponding to Nozzle 1 and 3 in Fig. 2.3). This causes the curling of the chip due to difference in the top and bottom surface temperatures. Thus, the chip-tool contact length is reduced, helping to reduce the cutting force and temperature and thus improving the tool life. In this system, the pressure of the cutting fluid was kept at 1.2 bar and the amount of cutting fluid was 5–10 ml/min. The pump was operated at 300–600 pulses/min. The system provided reduced surface finish, tool wear, cutting force, cutting temperature, and tool–chip contact length.

2.4 Minimum Quantity Lubrication with Nanofluids

Nanofluids are the fluids with a colloidal dispersion of nanometer-sizes particles of metals, oxides, carbides, nitrides, or nanotubes. Typically, a nanofluid may contain carbon nanotube (CNT), TiO_2, Al_2O_3, MoS_2, and diamond. Size of the nanoparticles is between 1 and 100 nm. Nanofluids show enhanced thermal conductivity and heat transfer coefficient. With the addition of nanoparticles, the thermal conductivity of the fluids can enhance by several hundred percents. This is mainly due to more surface-to-volume ratio of nanoparticles.

Recently, nanofluids have been used with MQL systems. The nanofluid is supplied to the machining area in the form of mist mixed with highly pressurized compressed air. Nanofluids have been containing MoS_2, diamond, and Al_2O_3 in grinding and milling. Nam et al. (2011) applied nanofluid containing 30-nm size diamond particles with the base fluids of paraffin and vegetable oils in microdrilling of aluminum 6061 workpiece. The performance of nanofluid MQL was compared with compressed air lubrication and pure MQL. The nanodiamond concentration of 1% and 2% by volume was considered for study. The addition of nanodiamond particles improved lubrication and cooling effects with their enhanced penetration and entrapment at the drilling interface. It is reported that nanoparticles have ball/rolling bearing effect and enhance tribological and wear characteristics significantly. As a result, the magnitude of torques and thrust forces were significantly reduced. The authors observed that paraffin oil based nanofluid MQL was more effective than the vegetable oil based one. In the case of the paraffin oil, the 1 vol% of nanodiamond particles was more effective than 2 vol% of particles. On the other hand, in the case of the vegetable oils, the nanofluid with 2 vol% was found better.

Authors attributed this to difference in the physical and chemical properties of two base fluids. In particular, the dynamic viscosity of vegetable oils is about 2–3 times higher than that of paraffin. Therefore, more nanoparticles could be needed for getting evenly spread in the drilling area. In the case of paraffin oils, 2 vol% may cause some nanodiamond particles to get clogged.

2.5 Minimum Quantity Lubrication: A Comparison with Other Systems

There is enough literature to show that MQL system provides better performance than dry machining. In many cases, it provides better performance than conventional flood coolant system. A brief representative review is provided in this section. When machining aluminum alloys, Kelly and Cotterell (2002) observed that as cutting speed and feed rate are increased, the use of a fluid mist outperformed the conventional flood coolant method, however, at lower cutting speed flood coolant system was superior. Braga et al. (2002) used a spray mist while drilling aluminum alloy and observed that surface finish and tool life was almost same in mist lubrication and flood coolant.

Mendes et al. (2006) studied the performance of drilling of AA 1050-O aluminum with TiAlN coated carbide drills and applied cutting fluid as mist. The cutting fluid flow rate was varied between 20 and 100 ml/h. It was observed that using the highest cutting fluid flow rate (100 ml/h) resulted in lower feed forces only at higher cutting speeds and feed rates. Power consumption and specific cutting pressure increased with cutting fluid flow rate and surface roughness was unaffected. This work shows that unnecessarily higher fluid flow rate is not useful. Davim et al. (2006) studied drilling of aluminum (AA1050) under dry, MQL and flood-lubricated conditions and concluded that with proper selection of cutting parameters, it is possible to obtain machining performance similar to flood-lubricated conditions by using MQL. Davim et al. (2007) made similar conclusion in turning of brasses using MQL.

In the turning of 6061 aluminum alloy with MQL, dry and flood lubricant conditions using diamond-coated carbide tools, Sreejith (2008) observed the superiority of MQL with 50 ml/h and 100 ml/h cutting fluid consumption. The tool wear was almost same as in the flood coolant system. The main cutting force was the lowest in the flood coolant system and the highest in dry machining. The surface roughness with 100 ml/h MQL was much lower than that obtained in dry machining. It was only slightly greater than the surface roughness obtained in flood coolant system.

Tawakoli et al. (2009) have investigated an MQL grinding or near dry grinding (NDG) system. In this system, an air–oil mixture called an aerosol is fed into the wheel-work zone. Compared to dry grinding, MQL grinding substantially enhances cutting performance in terms of increasing wheel life and improving the quality of the ground part. In the grinding of 100Cr6 hardened steel by Al_2O_3 grinding wheel, the surface roughness of ground part was lower than that in flood coolant system. However, in MQL grinding of 42CrMo4 soft steel, the surface roughness was higher than that in flood coolant system. In MQL grinding the cutting forces were lower than the dry and flood coolant systems. The wheel life was the best in MQL systems.

Alberdi et al. (2011) optimized the nozzle design in MQL grinding with the help of computational fluid dynamics. The optimized nozzle provides a more efficient coolant jet. The authors also proposed a technique based on the combination of MQL and low temperature CO_2 to assist grinding. The significant improvement in performance was obtained compared to other systems. The authors recommended that with the proposed system, the grinding wheels of higher porosity should be used for getting the best results.

2.6 Conclusion

From the discussion presented in this chapter, it is apparent that MQL systems possess many advantages over flood coolant system. However, they also require some modification of machine tools for obtaining the best performance out of them. When the flood coolant system is not present, the machine tools should be equipped with a chip removal system. There is also a requirement of fire and explosion system in the machining of light metal alloys like magnesium. There is additional cost involved in the equipment for MQL. A cost-benefit analysis is required before implementing MQL system.

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