# Chapter 18
# Bio-Based Nano-Lubricants for Sustainable Manufacturing

**Rahul Anand, Mir Irfan Ul Haq, and Ankush Raina**

## 18.1 Introduction

In today's contemporary manufacturing industry, there is rising demand of high productivity with low cost along with improved quality. In order to achieve the present production rate demand and challenge of cost competitiveness across the global markets, material removal rate should be enhanced. Increased material removal rate demands higher values of cutting parameters, i.e. speed, depth of cut and feed rate, which carry a great risk of tool wear and failure due to enormous heat generation and friction at cutting zone between chip and tool (Bruni et al. 2006). Plastic deformation also tends to deteriorate the surface integrity which is an important property in evaluation of productivity of machining processes (Davim et al. 2008). Chip flowing over the tool surface tends to carry the major portion of heat, and some portion is conducted by tool itself; thus reducing the temperature at cutting zone will largely enhance tool life and surface integrity and reduce tool deterioration (Dudzinski et al. 2004). Thus cutting fluids in modern industry act as an accessory in reducing the shear zone temperature by reducing chip tool contact length and improving the thermal conductivity at interface which greatly optimizes the cutting parameters and improved tool life (Vieira et al. 2001). Primary function of cutting fluid used in conventional machining is to simultaneously cool and lubricate the cutting zone thereby decreasing the coefficient of friction which in turn reduces the cutting forces required for conventional machining operations like turning, drilling, milling and grinding (Adler et al. 2006).

However issues related to excessive and conventional use of mineral oil-based cutting fluids have been debated by the researchers lately which involves disposal of toxic mineral oils in soil and water, and improper handling of mineral oil-based

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R. Anand · M. I. U. Haq (✉) · A. Raina
School of Mechanical Engineering, Shri Mata Vaishno Devi University,
Katra, Jammu & Kashmir, India

I. Bhushan et al. (eds.), *Nanomaterials and Environmental Biotechnology*,
Nanotechnology in the Life Sciences,
https://doi.org/10.1007/978-3-030-34544-0_18

cutting by machine operators may cause various health hazards and results in degradation of health of the operator (Soković and Mijanović 2001). Shashidhara and Jayaram (2010) estimated 80% of total health problems are caused due to mineral oil-based cutting fluids. Purchasing cost of cutting fluids includes 7–17% of total machining cost (Klocke and Eisenblätter 1997). European Union almost consumes annually 320 Mt of cutting fluids during machining processes out of which two thirds of used fluid has to be disposed (Lawal et al. 2013). Shokrani et al. (2012) estimated non-biodegradable mineral oil-based cutting fluid increases disposal cost fourfold the purchasing cost which also includes physical and chemical treatment cost required before disposing them.

Due to increased disposal, treatment cost and health and environmental problems, researchers are now investing their interest discovering biodegradable vegetable and esoteric oil (Tschätsch and Reichelt 2009). These vegetable and ester oils have biodegradability of 90–95% and have environmental compatibility in terms of biodegradability, toxicity, safe disposal and additives (Kodali and Nivens 2001; Pop et al. 2008). These vegetable oils provide a vast range of rheological properties in terms of flash point, viscosity index and low volatility. Debnath et al. (2014) listed out detailed developments in biodegradable vegetable-based cutting fluids and their influence on cutting parameters along with reduction in ecological and economical complications which were found in mineral oils. Simultaneously researchers are more focused on achieving more clean production by improving the methods cutting fluid applications at cutting zone (Fratila 2009). Dry machining can never be one solution to the problem as it affects tool life badly (Diniz and Micaroni 2002). So more convenient ways of near-dry machining (MQL) are now being adapted to minimize the use of cutting fluids. Sharma et al. (2009) talk about more such lubrication techniques (cryogenic cooling, MQL, flood and high-pressure cooling) during conventional machining processes which lead to clean and sustainable manufacturing. Lawal et al. (2013) in his research compared vegetable oil-based MQL lubrication technique and conventional flood lubrication and concluded that MQL with vegetable oil-based lubrication has better results than other conventional techniques in terms of process parameters and cost.

With technological advancements in manufacturing industry, nano-cutting fluids are now being imposed which profitably meet the challenge of heat dissipation during machining by providing stability and improved thermal conductivity to base oil at wide range of temperatures. These nano additives can be classified into metallic, non-metallic and nanofibres with diameter range up to 100 nm which are dispersed in base cutting oil (Chol and Estman 1995). Experimental research (Sharma et al. 2015b, 2016; Su et al. 2016) reveals these nanoparticles dispersed in base oil easily penetrate into cutting zones, and due to their heat extraction and friction reduction properties, they reduce too wear and cutting forces. MWCNT (multiwall carbon nanotubes) (Sharma et al. 2019), $Al_2O_3$ (aluminium oxide) (Arumugam et al. 2018), ZnO (zinc oxide) (Battez et al. 2008) and $MoS_2$ (molybdenum disulphide) (Rajendhran et al. 2018) are some of the nanoparticles which have improved thermal and tribological properties. Due to enhanced machining performance, addition of nanoparticles has minimized the use of cutting fluids, saving the environment and

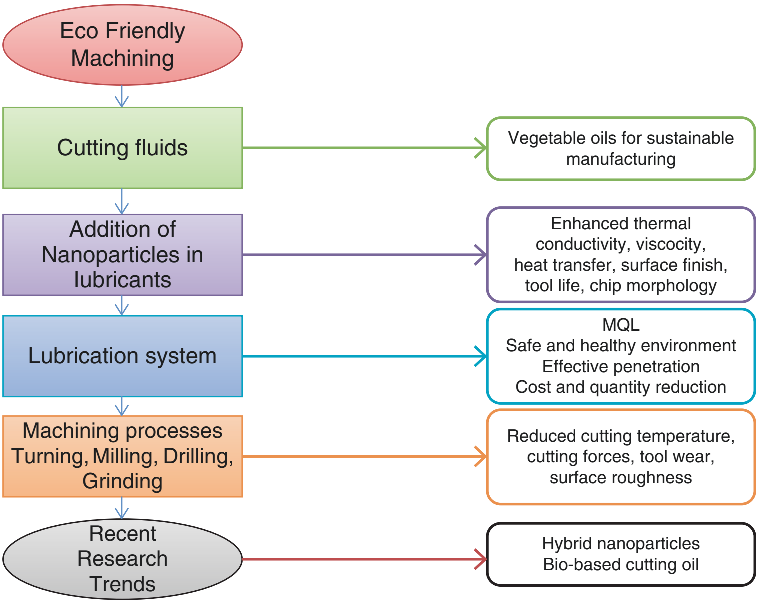


**Fig. 18.1** Flow chart representation of the machining processes involved

decreasing the cost of production. This paper widely discuss about vegetable oils and heat extraction and friction reduction mechanisms of nanofluids with MQL technique in conventional machining operations turning, drilling, milling and grinding (Fig. 18.1).

## *18.1.1 Types of Cutting Fluids*

El Baradie (1996) in his research classified cutting fluids along with their composition and also addressed issues like green machining, recycling of cutting fluids and their disposal.

### 18.1.1.1 Neat Cutting Oils

It mainly includes pure mineral oils or mineral oils with some load-carrying additives such as:

(a) Blends of mineral oil and fatty oil
(b) Blends of mineral oil and sulphurized fatty oil
(c) Blends of mineral oil and chlorofatty oil
(d) Blends of mineral oil and sulpho-chlorinated fatty oil
(e) Extreme pressure additives

#### 18.1.1.2 Water-Soluble Fluids

Water-soluble fluids are predominantly mineral oils blended with emulsifiers, and when this blend is added to water, an oil-in-water emulsion is produced which facilitates the high-speed cutting process because of its better cooling capabilities (). Water-soluble fluids are further classified as.

#### 18.1.1.3 Emulsifiable Oils

These are soluble oils made by blending the oil with emulsifying agents and other materials which form the dispersion phase in water for long period of time by breaking the oil into minute particles. These are further classified as:

(a) General purpose soluble oil (it includes nanoparticles-enriched cutting.)
(b) Clear type soluble oils
(c) Fatty soluble oils
(d) EP soluble oils

#### 18.1.1.4 Chemical (Synthetic Fluids)

These chemical coolants and lubricants include inorganic chemical agents dissolved in water with no mineral oil. It includes soaps and wetting agents for reduction in surface tension, nitrides for corrosion resistance, chlorine and sulphur for lubrication, glycols as blending agents and humectants and germicides to control bacterial growth.

#### 18.1.1.5 Semisynthetic Fluids

This type includes combination of chemical fluids and emulsifiable oils in water which forms stabilized emulsion with small droplet size that can facilitate heavy-duty machining.

### *18.1.2 Methods of Application of Cutting Fluids in Conventional Machining*

During machining of metals, conversion of energy to heat takes place in the regions of plastic deformation due to work involved in shearing the workpiece (da Silva and Wallbank 1999). High temperatures are thus produced on the cutting edges and chip tool interfaces which control the tool wear rate, tool life, MRR and surface finish of the material. Large part of this heat is conducted away by the chip, and the rest is conducted by the tool which acts as a sink. Researches have shown that on reducing the cutting, temperature will increase tool life and reduce the tool wear (Khan and Ahmed 2008). Cutting fluids are thus applied to carry away the heat from the cutting tool and workpiece interface thereby reducing the temperature which is critical for tool wear. 7–17% of the total cost of machining is acquired by the cutting fluid alone (Klocke and Eisenblätter 1997). Several techniques have been developed to increase the efficiency of cutting fluid and enhance the machining process by environment-friendly means.

Along with the improvement in the conventional cooling techniques and reduction in temperature rise, researchers have focused on environmental problems like disposability, toxicity, misting, staining and self-cleanliness involved using cutting fluids.

#### 18.1.2.1 Cryogenic Cooling

In cryogenic cooling liquid nitrogen (LN) is applied at cutting tool, workpiece or at the cutting zone in order to reduce the cutting temperature and enhance low-temperature machining (Evans and Bryan 1991). The nitrogen absorbs heat and evaporates to atmosphere thereby cooling the cutting edges of the tool and by forming a fluid gas layer between the chip and tool interface. Cryogenic cooling is an environmentally friendly and efficient way of maintaining a safe working temperature well below the critical or softening temperature of tool (Dhar et al. 2002). Thus reduction in temperature results in reduced flank and crater wear thereby improving the product quality and productivity. Cryogenic cooling is more predominant at lower cutting speed due to more effective penetration of cryogen between chip and tool interface (Khan and Ahmed 2008). Its cooling capability decreases with increase in cutting speed due to obstruction in penetration of cryogen in hot chip tool interface. Turning with carbide inserts with liquid nitrogen cryogenic cooling, it was observed that tool life improves which attributes to reduction in notching, abrasion, adhesion and diffusion type of wear.

#### 18.1.2.2 Solid Lubricant/Coolant

Use of conventional cutting fluids cause environmental pollution, ecological imbalance and serious biological hazards to workers along with increased cutting cost (Sreejith and Ngoi 2000; Tan et al. 2002). Now all these factors instigate researchers to avoid use of cutting fluids with some other cooling methods. Solid lubrication is one of the techniques which strive to minimize the use of cutting fluid (Shaji and Radhakrishnan 2003). Molybdenum disulphide ($MoS_2$) and graphite are most commonly used solid lubricants due to their lamellar structure; these lamellas incline between loaded surfaces and glide over each other in order to reduce friction and contact. Boron nitride, calcium fluoride and tungsten disulphide are other materials which can be used. During turning of AISI 52100 steel at high speed of 125 m/s, it was observed that due to layered lattice structure, cutting forces were minimized, and due to good adhesion property of molybdenum disulphide, lower value of surface roughness (13–15% reduction) than graphite (7–10% reduction) was observed (Dilbag and Rao 2008; Lathkar and Bas 2000).

#### 18.1.2.3 High-Pressure Cooling Technique

High-pressure coolant delivery technique allows the coolant to penetrate in tool-chip and tool-workpiece interface thereby enhancing the cooling effect and lowering the tool wear rate by effectively lubricating the contact regions (Diniz and Micaroni 2007; Wertheim et al. 1992). Pressurized coolant thus forms a hydraulic layer of wedge shape between tool-workpiece interface which facilitates high-speed machining (Mazurkiewicz et al. 1989). Researchers have found that pressurized coolant not only increase the effectiveness of cooling but also reduce the chip tool contact time by taking the chip off the rake surface thereby significantly improving the tool life (Ezugwu and Bonney 2005). Turning titanium under high-pressure conditions reduces chip tool interface temperature and cutting forces and improves surface roughness as chip tool contact time is reduced (De Lacalle et al. 2000). Cutting forces significantly reduce cutting forces while machining Inconel 718 alloy due to improved lubrication at tool-workpiece interface (Ezugwu et al. 2005).

#### 18.1.2.4 Air/Vapour/Gas Cooling

For protection of ecology and environment, the use of green cutting fluids has become a major concern in machining. Water vapour and gas emerge as best alternatives for cooling and lubrication than conventional synthetic cutting fluids. Liquid Nitrogen and Nitrogen gas at high pressure serve best operating conditions for machining. Application of nitrogen, oxygen and $CO_2$ provides lower cutting forces than dry and wet cooling operations with reduced surface roughness (Altan et al. 2002; Çakıra et al. 2004; Godlevski et al. 1998). Mist application of air-oil at 0 °C provides simultaneous effect of cooling and lubrication which reduces wear by 13% as compared to air-jet cooling (Ko et al. 1999). During machining of the AISI 1045 steel (in presence of nitrogen gas, water vapour, mixture of gas and water vapour), water vapour alleviate friction by filling up the cavities in the cutting zone by capillary action which thus improves tool life twice than dry machining (Liu et al. 2007). During turning of En32b plain carbon steel, the nitrogen gas provided the best cutting conditions with reduced crater (55%) and flank wear (30%) than dry machining by reducing the chip tool contact length (Stanford et al. 2009).

#### 18.1.2.5 Minimum Quantity Lubrication

MQL (minimum quantity lubrication) also referred as near-dry machining or micro-machining is an environmental-friendly alternative to flood and dry machining. Lubricant is mixed with air and is injected on the cutting surfaces through different techniques (Varadarajan et al. 2002). MQL is the best lubrication technique that leads to clean and sustainable production along with better heat convection, tool life and surface finish and improved chip morphology (Philip et al. 2001; Wertheim et al. 1992). Lubricant is either mixed inside or outside the nozzle with compressed air to form an aerosol which is applied to the cutting interface with the help of the nozzle with industrial range of 10–100 ml/h (Kamata and Obikawa 2007). Biodegradable vegetable oils as cutting fluids are preferred because of their superior lubrication performance at high pressure. MQL helps in reducing wear that are sensitive to temperature (abrasion wear and diffusion wear) thereby maintaining the hardness and reducing the notch growth in tool. In investigations it was observed that chip tool contact length and cutting forces reduced with MQL technique than conventional dry and wet turning. MQL of air-oil mixture when sprayed at 0.276 Mpa through 0.762 mm via nozzle at low cutting speed reduces tangential cutting force by 26.6% than in dry machining and 32.2% of that in flood cooling (Li and Liang 2007).

#### 18.1.2.6 Nano-Enriched Cutting Fluids

Researchers have investigated that addition of nanoparticles enhance the machining and tribological properties of the cutting fluids. Nanoparticles with properties like rolling, sliding and filming action ensure better lubrication thereby reducing power consumption and cutting forces. Observations also tell that addition of nanoparticles not only penetrates inside shearing zone but also increases heat transfer capability of the cutting fluid as nanoparticles have much higher thermal conductivity than liquid alone as shown in the table. Nanoparticles with MQL lubrication technique are now being investigated as new research trend in the field of lubrication.

### *18.1.3 MQL (Minimum Quantity Lubrication) Application Technique*

MQL technique involves spraying mixture of lubricant with air at a high pressure at machining zone with help of nozzle (Duchosal et al. 2013). MQL system consists of nozzle jet to spray the air-oil mixture, pressure gauges and oil reservoir. Due to the venture effect, a vacuum is created inside the mixing chamber which sucks the lubricating oil from the oil sump (Khan et al. 2009). The compressed air passing through the chamber atomizes the lubricant stream into fine aerosol micron-sized particles which is sprayed in cutting zones as mist by the nozzle. It effectively acts as a coolant and penetrates deep into the tool-workpiece interface.

There are two main methods of cutting fluid application to the machining zones in MQL.

#### 18.1.3.1 Internal Application

In this application the oil and compressed air are applied to the cutting zone interface through tool itself. It's also called as through-tool application. Further it is also divided into two types.

(i) *Single channel*: In this system of MQL technique, compressed air and oil are mixed in mixing chamber before being supplied through cutting tool to machining zone.
(ii) *Dual channel*: Compressed air with cutting fluid in this delivery system are differently supplied and are mixed just before the machining zone.

#### 18.1.3.2 External Application

In this application the oil and compressed gas are applied to the cutting zone through external nozzle arrangement. Furthermore there are two more methods of external application.

(i) *Ejector nozzle*: The oil and compressed air are supplied differently, and atomization takes place just outside the nozzle.
(ii) *Conventional nozzle*: Micro-sized fine aerosol mist is made in external atomizer and is then sprayed through the conventional nozzle.

Zeilmann and Weingaertner (2006) investigated the effect of external and internal delivery applications on drilling temperature by drilling titanium alloy (Ti-6AL-4V). It was observed that temperature rise in internal delivery system was 50% less than external delivery system due to improper penetration of externally supplied aerosol mixture. Tsao (2007) on milling aluminium alloy (A6061P-T651) investigated that using sulphurous boric acid cutting fluid in MQL reduces average flank wear by 12.5% compared to dry milling. Along with flank wear, surface finish and tool life also improved using MQL tan wet and dry machining using different types of carbide tools (Kamata and Obikawa 2007). Kishawy et al. (2005) investigated cutting forces and wear and surface roughness conditions in both MQL flood and dry lubrication. MQL showed preferable results over dry machining due to its economic and environmental advantages.

## 18.2 Vegetable Oil-Based Lubricants

### *18.2.1 Physicochemical Properties of Vegetable Oil-Based Lubricants*

Bio-based lubricants which are usually vegetable oils and other natural sources possess less toxicity and eco-friendly biodegradability. Vegetable oils which can be edible and nonedible and which differ in geographical and tropical regions of the world can be used as bio-lubricants. Main emphasis nowadays is laid on nonedible vegetable oils which are considered as unused crops (Atabani et al. 2013). Principal component of these vegetable oils is triacylglycerols which constitute 98% composition followed by diglycerols and fatty acids (Rudnick 2005). This triglyceride structure is responsible for structural stability and high viscosity at high machining temperatures.

#### 18.2.1.1 Viscosity

Viscosity plays an important role in reducing wear and metal-to-metal contact (Salimon et al. 2010). High viscosity measures more resistance to flow, and less viscous lubricant has less resistance to flow (Mobarak et al. 2014). Long carbon chain length, compact branched and saturated structure enhance the viscosity of the oil (Knothe and Steidley 2005; Rudnick 2005). There are various modification techniques through which viscosity of the vegetable oils can be improved to sustain viscous properties at higher machining temperatures. Presence of one double bond will increase the viscosity of oil, whereas presence of two or more double bonds will decrease the viscosity (Rodrigues et al. 2006). Epoxidized soybean oil possesses high viscosity at extreme cutting temperatures than other vegetable oils (Ting and Chen 2011).

#### 18.2.1.2 Viscosity Index

It is the measure of variation in viscosity with temperature. The higher the viscosity index of oil, the lower is the variation with increase temperature. Oil having high viscosity index will maintain the thickness of the film at higher temperatures which reduces wear and enhances cutting conditions (Masjuki et al. 1999). Generally vegetable oils possess high viscosity index than mineral oils. Canola, palm oil-based lubricants, showed higher viscosity index than mineral-based cutting oils due to their enhanced intermolecular interactions and polyunsaturated structure (Sripada et al. 2013).

#### 18.2.1.3 Flash Point

Flash point is an important property of a lubricant which refers to the lowest temperature at which a particular lubricant will turn to form vapours. Higher flash point thus minimizes the risk of leakage and thus provides safe machining operation at various range of temperatures (Gnanasekaran and Chavidi 2018).

#### 18.2.1.4 Pour Point

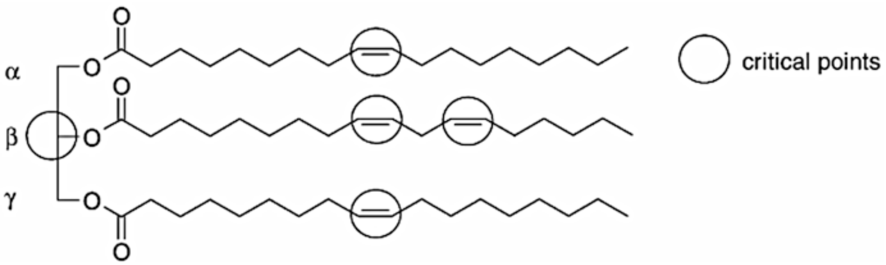
Pour point is another important characteristic of lubricating oil which is defined as lowest temperature at which lubricant will become semi-solid and loses its ability to flow. Thus lubricants with low flash point are more suitable for machining at low temperatures (Benchaita and Lockwood 1993). If lubricant doesn’t possess low pour point property, the lubricant will cease to flow at low temperature and will increase friction and wear during machining. For most of the vegetable oil pour point is lower than −10 °C which results in poor flow of oil at low temperatures due to bending and continuous stacking of triglyceride structure and formation of macro-crystals (Asadauskas and Erhan 1999; Quinchia et al. 2012; Rhee et al. 1995). These crystal structures and strong intermolecular bonding sometimes cease the ability of oil to flow at low temperatures which attributes to loss in kinetic energy due to self-stacking (Erhan et al. 2006). Oils that have more unsaturated fatty chains will have lower pour points; rapeseed oil (−21 °C) has lower pour point than olive oil (−10 °C) due to increased unsaturated fatty chains which restricts the formation of packed crystals during cooling (Gryglewicz et al. 2003).

#### 18.2.1.5 Oxidation Stability

Oxidation stability of a lubricant refers to the capability of the vegetable oil to resist reaction with oxygen, the rate of which is also influenced by pressure, temperature and presence of impurities (Mobarak et al. 2014). A lubricant should possess high oxidative stability as low oxidation stability may lead to polymerization which increases viscosity and degrades the functional properties of lubricant on machining (Asadauskas et al. 1996; Lal and Carrick 1994; Suda et al. 2002). Critical factor that influences the oxidation stability is the presence of polyunsaturated compounds in the molecular chains which can easily react with oxygen from oxides, peroxides and acids (Wu et al. 2000). Thus the higher is the unsaturation, the more is the chance of oxidation (Fox and Stachowiak 2007). Removal of β-CH group allows the formation of carboxylic acid which deteriorates the quality of lubricating oil (Zulkifli et al. 2014).

**Table 18.1** Physicochemical properties of different vegetable oils

| Vegetable oil | Viscosity 40 °C ($mm^2/s$) | Density × $10^3$ $kg/m^3$ | Flash point (°C) | Pour point (°C) | Viscosity index |
|---|---|---|---|---|---|
| Sunflower oil (Rac and Vencl 2009) | 47.6 | 0.917 | 245 | −20 | 218 |
| Rapeseed oil (Arumugam and Sriram 2013) | 35.0 | 0.930 | 320 | −10 | 220 |
| Palm oil (Barnwal and Sharma 2005) | 39.6 | 0.918 | 267 | – | – |
| Soybean oil (Honary 1996) | 29.0 | 0.913 | 328 | −10 | 246 |
| Jatropha oil (Mofijur et al. 2012) | 35.4 | 0.918 | 186 | | – |
| Karanja oil (Bobade and Khyade 2012) | 40.2 | 0.924 | 225 | −3 | – |
| Coconut oil (Nakpong and Wootthikanokkhan 2010) | 28.1 | 0.920 | – | – | – |
| Safflower oil (Singh and Singh 2010) | 31.3 | 0.914 | 260 | −06.7 | – |
| Calophyllum inophyllum oil (Atabani et al. 2013; Habibullah et al. 2015) | 71.9 | 0.896 | 221 | 4.3 | |



Plant oil-glycerine ester consists of different fatty acids with critical points and β-CH group (Wagner et al. 2001) (Table 18.1).

## 18.3 Role of Nanoparticles in Cutting Fluids

In recent approaches in order to increase the lubricity of base oil in MQL, scientists have used nanoparticles along with base oil which significantly improve thermal and heat transfer capabilities, reduce frictional coefficient and increase load-bearing capabilities of the mechanical systems. Adhesion and stress concentration were reduced to a large extent with the help of nano-cutting fluid thereby reducing mechanical failure and wear (Chang and Friedrich 2010). Sharma et al. studied improved thermophysical properties and reduced cutting forces, surface roughness and tool wear relative to base fluid used alone which improved machine performance (Sharma et al. 2015a). Kumar et al. (2012) recorded that increase in concentration of nanoparticles increases thermal conductivity which reduces the cutting zone temperature by easy extraction of heat from cutting zone. A variety of mechanisms that are involved in the enhancement of lubrication properties of the cutting fluid have been explored.

## *18.3.1 Mechanism of Nanolubrication*

### 18.3.1.1 Ball Bearing/Rolling/Sliding Effect

Rapoport et al. (2002) investigated layered materials like graphite; $MoS_2$ when used as nano additives in cutting fluids eliminate the metal-to-metal contact between asperities due to their slippery nature that leads to fast displacement from contact area. Such effect facilitates the shearing nature of the cutting fluids. Wu et al. (2007) studied the transition from sliding to rolling friction and deposition of nanoparticles (CuO) in the worn surfaces which decreases the shear stress and improves the tribological property of cutting fluids.

### 18.3.1.2 Polishing Mechanism

It is a surface enhancement phenomenon in which nanoparticles penetrate into rubbing surfaces and polish the surface which decrease the contact wear of mating surfaces. Tao et al. (1996) studied the polishing effect of diamond nanoparticles dispersed in paraffin oil which increased the hardness of the rubbing surface than the test material. Lee et al. (2009b) studied the surface enhancement property of the nano oil by comparing the friction coefficient of disc type specimen dipped in mineral oil and nano oil.

### 18.3.1.3 Mending Mechanism

The nanoparticles accumulate over the contact surface and compensate for the lost mass on the contact surface thereby reducing the wear scars resulting in smooth surface (Lee et al. 2009a). Liu et al. (2004) investigated the mending effect and mechanism of copper nanoparticles on pin-on-desk setup. SEM and STM observations exhibit the presence of copper in the worn-out areas thereby reflecting the contribution of mending effect.

### 18.3.1.4 Formation of Tribofilm

This process produces a protective film over the mating surfaces. Nanoparticles on reacting with the surface layer of the material produce some tiny secondary particles which help in smoothening of nano bumps on the mating surfaces (Gupta and Harsha 2018). Hu et al. (2002) demonstrated the tribofilm formation by adding magnesium borate (10 nm) in SN 500 oil which reduced the coefficient of friction and surface wear by forming the protective wear film over the mating surfaces.

## *18.3.2 Preparation of Nanofluids*

### 18.3.2.1 Two-Step Method

Most common method for the preparation of nanofluids is two-step method in which powder form with specific size of nanotubes and nanoparticles are produced as first step. During second step mixing of these nanoparticles is carried out in the base fluid directly with the help of magnetic stirrer, ultrasonic devices or homogenizer (Drzazga Michałand Dzido et al. 2012; Duangthongsuk and Wongwises 2009; Hwang et al. 2007; Khairul et al. 2014; Manimaran et al. 2014). Two-step method works well with oxide nanoparticles and metallic nanoparticles as well (Manna 2012). $Al_2O_3$/water and $TiO_2$/water nanofluids were prepared using two-step method of nanofluid preparation (Chon et al. 2005; Haghighi et al. 2013; Li et al. 2008; Murshed et al. 2005; Wang et al. 2009). Li et al. (2008) using two-step method prepared Cu/water fluid to check the influence of pH value and surfactant addition on thermal conductivity. By two-step method, preparation of nanofluids on mass scale is possible which has already increased the rate production in industries; however problem of transportation and storage cannot be avoided in this process (Yu et al. 2012). Formation of agglomerates due to high surface energy of nanoparticles is also a major disadvantage of two-step method which is further improved by one-step method in preparation of nanofluids (Mohammed et al. 2011). However two-step method can be used to form nanofluid solution with any base fluid (Wang and Mujumdar 2007).

### 18.3.2.2 One-Step Method

One-step method combines both production and deposition of nanoparticles as nanofluids. In this method of preparation, problem of storage and transportation is ward off, and agglomeration of nanoparticles is minimized which enhances the stability of nanoparticles (Li et al. 2009). In one-step process, nanofluid is directly prepared by physical vapour deposition (PVD) technique or by condensation technique known as VEROS (vacuum evaporation onto a running oil substrate) (Akoh et al. 1978). Eastman et al. (1996) directly dispersed the vapours of condensed metal to nanoparticles in the base fluid thereby modifying the VEROS technique of one-step method. Direct evaporation and condensation of one-step method developed by Choi et al. (2002) provides enhanced stability and largely controls the size of nanoparticles. Lo et al. (2005) introduced a submerged arc nanoparticle synthesis system (SANSS) using two different dielectric liquids which enhances stability and minimizes agglomeration effectively. Nanoparticles produced are of polygonal, square, circular and needle-like shape. Later on Chang and Kao (Chang and Kao 2007) modified this technique and improved the nanoparticle synthesis both quantitatively and qualitatively. Disadvantage of this method is residual reactants that are left after incomplete reaction later arise as impurity in nanofluid solution, and other disadvantage is its compatibility with low vapour pressure base fluids only (Wang and Mujumdar 2007).

### *18.3.3 Importance of Nanofluid Stability*

Stability of nanoparticles means nanoparticles do not tend to agglomerate with passage of time at a significant rate (Yu et al. 2012). Stability is hence susceptibility of nanoparticles to agglomerate due to high surface energy which not only blocks microchannels but also influence thermophysical properties like thermal conductivity, density and viscosity with time (Ghadimi et al. 2011). Rate of agglomeration depends on the frequency of collision and probability of cohesion during collision due to *Brownian motion*. Stability of nanoparticles is the basic requirement for its wide application and utilization. Stability of nanofluids depends on preparation method, type of base fluids, sonication time and added surfactants. Stability is achieved when electrostatic repulsive forces between the nanoparticles are higher than attractive forces (Missana and Adell 2000; Popa et al. 2010). Agglomeration is generally reduced by steric and electrostatic mechanisms. In steric stabilization mechanism, additives like surfactants are added which form a protective layer over the nanoparticle and cease its ability to agglomerate or collide with other nanoparticle (Zhu et al. 2007). In electrostatic stabilization adsorption of ions create an ionic layer over the nanoparticle surface which enhances the repulsive forces between nanoparticles thereby increasing the stability of nanofluid (Mukherjee and Paria 2013) (Fig. 18.2).

## 18.4 Nanoparticle-Enriched Cutting Using MQL

### *18.4.1 MQL-Assisted Drilling with Nanoparticles*

Minimum quantity of lubrication has largely reduced cost of machining and has enhanced machining parameters on large scale. Attempts to reduce the use of cutting fluid in machining are turning out to be a good alternative than flood and dry machining. MQL drilling is found out more promising than dry and wet conditions for low aspect ratio, and with further modifications in supply and cutting fluid, high aspect ratios can be achieved by Mathew and Vijayaraghavan (2017). Nam et al. (2011) studied the characteristics of nanofluid micro-drilling using MQL on aluminium 6061. Varying the concentration of nanodiamonds and type of base fluid, it

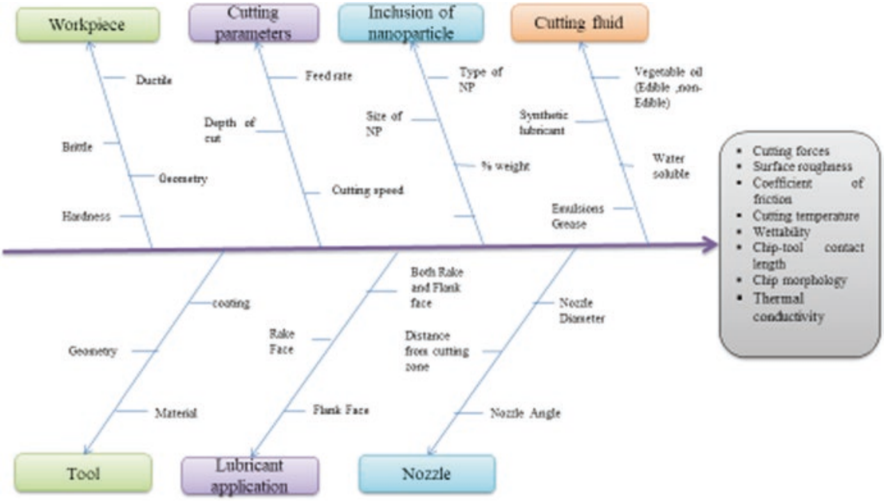


**Fig. 18.2** Fishbone diagram representation of various parameters involved in MQL-assisted machining

was observed that nanodiamond-enriched MQL improves the quality of holes and lubrication which attributes to rolling, ball bearing and cooling characteristics of nanoparticles. Furthermore 1% of nanodiamond was more effective in reduction of torque and thrust forces than 2% of nanodiamond. Huang et al. (2016) analysed the micro-drilling operation with different drilling conditions. It was concluded that applying nanodiamonds in vegetable oil with MQL reduces the machining zone temperature due to improved heat transfer rate by nanoparticles. Application of nanoparticles also reduces the burr around the holes improving the quality of holes. Addition of nanoparticles reduces forces and torque required for drilling thereby improving the tool life of drill. Nam et al. (2015) conducted 25 experiments by multi-optimization techniques (RSM and GA) and deduced that minimum thrust, and torque forces at high spindle speed were obtained at 2 vol% of nanodiamonds in conventional oil. Considering same parameters (drill diameter, spindle speed, feed direction and concentration), Chai et al. (2016) dispersed MWCNT in hydrogenated oil using surfactants. TEM and FTR results analysis shows increase in thermal conductivity with some abrupt changes at different temperatures. 9.8% increase in thermal conductivity by adding 100 ppm nanoparticles at 50 °C was the highest observed value. Chatha et al. (2016) investigated influence of $Al_2O_3$ mixed nanofluid (1.5 vol%) on drilling 6063 aluminium with HSS tool. Addition of nanoparticles showed better machining results in terms of surface roughness, cutting speed and thrust forces as compared to dry, flood and pure MQL conditions due to their enhanced lubricating and cooling characteristics. Furthermore increase in number of holes drilled and reduction in chip contact length were observed with nanofluid MQL machining than dry and pure MQL machining. Garg et al. (2016) performed computational modelling using different techniques (ANFIS and GP), and relation between feed rate, drill diameter and MRR was established. For lower values of torque and thrust forces, drill diameter was critical parameter.

Mosleh et al. (2017) experimentally compared performance of nanodiamond (ND) and molybdenum disulphide ($MoS_2$) in alcohol-based lubricant under extreme pressure test. Results showed that addition of $MoS_2$ increases load-carrying capacity by 16% and increases service life of tool by 25%; on the other hand, dispersion of nanodiamond in base oil reduced the service life and has unfavourable response on tribological and lubrication properties of nanofluid. There is increase in tool life with addition of $MoS_2$ by 25%, while ND mixed nanofluid deteriorates both lubrication and tribological properties. Addition of $TiO_2$ nanoparticles increases heat transfer and lowers the drilling temperature at interface as compared to dry and base fluids (Salimi-Yasar et al. 2017). Nam and Lee (2018) investigated influence of nanodiamonds in vegetable oil on machinability of titanium alloy (Ti-6Al-4V). Results showed that nanodiamonds (35 nm) at low feed rate (10 mm) penetrate deep into drilling zones and provide ball-bearing effect which reduces the thrust force and torque required. Chip adhesion with drill surface and burr formation significantly reduced (Table. 18.2).

### *18.4.2 MQL-Assisted Grinding with Nanoparticles*

Shen et al. (2008b) studied the influence of $Al_2O_3$-enriched nanofluid in grinding cast iron with MQL. Different modes of lubrication, dry, flooded, pure water, synthetic oil (5 vol%) with MQL, water-based MQL with $Al_2O_3$ and ND nanofluid of 1.5 vol%, were experimentally used in this study. It was observed that grinding ratio increases with larger fractions of $Al_2O_3$ (4 vol%) due to formation of tribofilm between grinding wheel and workpiece. MQL with Cimtech 500 outperformed other modes of lubrication in reducing surface roughness. 2.5% $Al_2O_3$ provided better surface finish than any other concentration in base fluid. Furthermore nanodiamond-rich nanofluid provided better results than $Al_2O_3$-rich nanofluid. On increasing flow rate in MQL, cooling rates at grinding interface can be enhanced.

Using same setup as Shen et al. (2008a, b), investigated effect of $MoS_2$ nanoparticles in grinding using paraffin oil, soybean oil and CANMIST as base oil with MQL lubrication technique. It was recorded that $MoS_2$ with CANMIST oil reduces grinding force by 27% thereby improving G-ratio by 46%, superior of all other base fluids.

Alberts et al. (2009) investigated experimentally the effect of nanofluid with varying size of graphite nanoparticles (xGnP) on machining D2 steel with MQL mode of lubrication. It was observed that large-size nanoparticles (15 μm) effectively reduce grinding forces, surface roughness and grinding energy than small-size nanoparticles (1 μm).

Kalita et al. (2010) studied the grinding performance of soybean mixed with $MoS_2$ nanofluid. 25% reduction in coefficient of friction was recorded with nano-mixed MQL as compared to flood lubrication and 10% reduction as compared to

**Table 18.2** Literature review of MQL-assisted drilling with nanoparticles

| Author | Base fluid | Nanoparticle (size) | Workpiece | Parameters | | | Mode of nanofluid supply | Process findings |
|---|---|---|---|---|---|---|---|---|
| | | | | Cutting speed | Depth of Cut | Feed rate | | |
| Nam et al. (2011) | Paraffin and vegetable oil | ND (30 nm) | Aluminium 6061 | 60,000 RPM | 0.4 mm | 50 mm/min | MQL | No. of holes drilled increased with use of nanofluid due to enhanced cooling and lubrication rate<br>In order to reduce drilling torques and thrust forces, 1% of ND was effective than 2% of ND |
| Huang et al. (2016) | Vegetable oil | ND (<100 nm) | Aluminium alloy 7075-T6 | 48,000 RPM | 0.52 mm | 8 μm/rev | MQL | Addition of (2 wt%) of nanofluid reduces the drilling torque and improves hole quality by reducing the burrs |
| Nam et al. (2015) | Paraffin and vegetable oil | ND (30 nm) | Aluminium | 60,000 RPM<br>45,000 RPM<br>30,000 RPM | – | 15 mm/min | MQL | |
| Chai et al. (2016) | Hydrogenated oil | MWCNT (10–12 nm) | Steel | 1800 RPM | 20 mm | 0.02 m/min | – | A 10% increase in thermal conductivity was observed with a very less addition of nanoparticles in the base fluid |
| Chatha et al. (2016) | Soybean oil | $Al_2O_3$ (20 nm) | Aluminium 6063 | 30, 53.7 m/min | 20 mm | 60 mm/min | MQL | HSS drills drilled nearly 200 holes with less burr formation in MQL and flooded lubrication in response to 27 in dry drilling<br>Nanoparticles along with vegetable oil enhance the lubrication properties and reduce friction and wear thereby forming as protective coating on the surface |

(continued)

**Table 18.2** (continued)

| Author | Base fluid | Nanoparticle (size) | Workpiece | Parameters | | | Mode of nanofluid supply | Process findings |
|---|---|---|---|---|---|---|---|---|
| | | | | Cutting speed | Depth of Cut | Feed rate | | |
| Mosleh et al. (2017) | Boelube oil 70,104 | $MoS_2$ (70–100 nm)<br>ND (3–7 nm) | 4340 steel | 9.144 m/min | – | 0.63 mm/min | – | 2–4% by weight concentration of $MoS_2$ increased the load-carrying capacity up to 16% of base fluid<br>0.5–1% by weight concentration of ND enhanced the tribological and lubricity of base fluid thereby increasing tool life by 25% |
| Garg et al. (2016) | Vegetable oil | ND (nanodiamond) | Aluminium | 60,000 RPM<br>45,000 RPM<br>30,000 RPM | | 15 mm/min<br>12.5 mm/min<br>10 mm/min | MQL | Drill diameter and feed rate were optimized as critical parameters for higher MRR |
| Salimi-Yasar et al. (2017) | Soluble oil | $TiO_2$ (20 nm) | Steel | 1800 RPM | 20 mm | 0.02 m/min | – | Addition of $TiO_2$ enhances the thermal and lubricating properties with increased heat transfer rate than base fluid alone |
| Nam and Lee (2018) | Vegetable oil | ND (35, 80) | Ti-6Al-4V | 60,000 RPM | 0.4 mm | 10 mm/min | MQL | Small size (35 nm), high weight concentration 0.4% and low feed rate 10 mm/min enhanced machinability<br>Burr formation and chip adhesion were minimized due to bearing characteristic of nanoparticles at drilling zone |

pure MQL using soybean. Furthermore SEM and EDS analysis confirmed presence of Mo-S-P multilayer and tribolayer that reduces frictional wear between machining surfaces and enhances G-ratio without reducing material removal rate.

Kalita et al. (2012a) using EN24 and cast iron as working material studied the influence of $MoS_2$-rich paraffin oil and soybean oil under different lubricating conditions. 50% increase in G-ratio along with reduction of frictional coefficient (min 0.22) and 53% reduction in energy consumption was observed with both soybean and paraffin oil-based MQL lubrication. Changing the abrasive size on grinding wheel on same setup as 508–356 μm (Kalita et al. 2012b) recorded 48–52% reduction in force ratio along with reduction of peak temperature of cutting zone by 8.5% on addition of 2 wt% of nanoparticles. X-ray and SEM microanalysis showed the presence of plate-like lamella of Mo-S-P layers (molybdenum sulphur phosphorus tribofilm) thereby providing enhance lubricating properties by shearing and rolling mechanisms.

Prabhu et al. (2015) using fuzzy logic neutral technique analysed the surface roughness and microcracks on machining D3 tool steel. Using ANOVA analysis it was observed that cutting speed was the most important factor (65.1% with CNT and 58.38% with/without CNT) that influence the surface roughness of steel workpiece. Addition of MWCNT improved the surface roughness and microcracks. ANN model developed produces surface roughness close to actual value with minimum error of 0.88–9.3% and hence can be used to record surface finish values before machining.

Vasu and Kumar (2011) experimentally studied the influence of adding $Al_2O_3$ nanoparticles with emulsifier as base fluid on machining steel EN-31 workpiece. 20–30% reduction in machining temperature was observed at wheel workpiece interface. FEM model used records that 1% addition of $Al_2O_3$ reduces surface roughness and energy partition.

Prabhu and Vinayagam (2012) using Taguchi analysis investigated the influence of CNT nanoparticles in grinding AISI D3 tool steel. Depth of cut, spindle speed and feed rate were considered as design factors, and eight experiments were performed using $L_8$ orthogonal array. Minimum surface roughness (0.4478 μm) was recorded using CNT nanofluid, and crack width recorded with CNT also reduced from 2.22 to 1.93 mm. Using same setup as Vasu and Kumar (2011), Lee et al. (2012) considering antitoxic and super tribological properties of nanodiamond and $Al_2O_3$ mixed them with 150 and 20 nm each at 4% and 3% vol each in paraffin oil. Results of machining were compared with dry and pure oil-based MQL lubrication conditions. MQL with nanofluid was more effective in reducing cutting forces than dry and pure MQL. High concentration along with small diameter of nanoparticle reduces cutting forces significantly. Furthermore large size of nanoparticle effectively reduces surface roughness.

Mao et al. (2012) experimentally studied the performance of $Al_2O_3$ nanofluid with MQL technique on machining AISI 52100 hardened steel with aluminium oxide abrasive grinding wheel. Reduction in cutting zone temperature (40%), decrease in grinding forces and improved surface morphology was recorded with $Al_2O_3$ nanofluid MQL than pure water MQL grinding. Furthermore ball bearing and rolling mechanisms of nanoparticles effectively enhance lubricating and cooling conditions at cutting zone.

Mao et al. (2013b) also investigated influence of air pressure and nozzle angle during machining with $Al_2O_3$ nanofluids. Spraying parameter (0.2, 0.4, 0.6, 0.8 MPa) pressure with nozzle direction and spraying distance 20, 40 and 60 mm were used experimentally. It was observed that optimized parameters can be obtained with nozzle set at 15° with horizontal than tangential or directly towards wheel.

Prabhu and Vinayagam (2013) investigated effect of grinding glass with SWCNT using water as base fluid in MQL system of lubrication. Electrolytic process technique (ELID) was used with metal-bonded diamond grinding wheel for machining. Reduction in surface roughness and microcracks from 0.3758 to 0.1791 μm and 2.88 to 1.58 was calculated with atomic force microscopy.

Mao et al. (2013a) concluded that higher concentration (1, 3, 5 vol%) of $Al_2O_3$ nanoparticles reduces grinding forces (2.32, 2.19, 2.12 N/mm). It was further investigated that oil-based $MoS_2$ require lower grinding force than water-based nanofluid in MQL-based nanofluid machining.

Li et al. (2013) studied surface heat generation on the surface of three workpiece (45 steel, 2Cr13, zirconia ceramics) through numerical simulation. Grinding operation was performed under three lubricating conditions: dry, flood cooling and oil-based pure MQL and MQL with CNT nanoparticles. It was observed that CNT nanofluid with MQL effectively reduces the surface temperature than any other mode of lubrication thereby enhancing the surface quality and minimizing the burns on the surface of grinding wheel. Addition of surfactant (SDBS) reduced the chance of agglomeration and enhanced cooling and lubrication properties of the nanofluid.

Jia et al. (2014) experimentally investigated influence of machining with nanofluid of $MoS_2$, PCD (polycrystalline diamond) and $ZrO_2$ nanoparticles using MQL technique. Results were compared with dry, water-based flood cooling, pure MQL using soybean oil and nanoparticle with mixed MQL. It was observed that tangential forces decreased by 45.88% in pure MQL grinding, 62.34% in nanofluid-based MQL and 69.33% in flood grinding. Furthermore it was observed that $MoS_2$ forms a physical layer of molybdenum trioxide on the surface which reduces the load-carrying capacity at the grinding zone.

Wang et al. (2014) studied the relationship between crack formation and surface morphology of the workpiece (quenched 45 steel) using $MoS_2$ nanofluid-based MQL technique through mathematical model. Bump height reduces with increase in speed and with increase in number of cracks, whereas when a number of cracks reduce with increase in peripheral speed, the bump height increases with increasing crack length. Experimental values were smaller than simulated values which attributes to cooling and lubrication effects of nanoparticles.

ManojKumar and Ghosh (2015) investigated performance of MWCNT mixed nanofluid in machining of AISI 52100 steel using small amount of cutting fluid lubrication (SQL). Results of dry, oil-based flood lubrication, oil-based SQL and nanofluid mixed SQL were compared. It was observed that enhanced thermal conductivity which improved chip morphology and minimum coefficient of friction (0.07) was recorded with 1 vol% of MWCNT. G-ratio improved with MWCNT nanofluid, and results of surface roughness were comparable with flood lubrication using SQL.

Mao et al. (2014a) performed grinding of AISI 52100 steel with nanofluid using MQL technique. Canola oil as cutting fluid, dry, deionized water, $Al_2O_3$ with MQL and $MoS_2$ with MQL were used for experiments. It was observed that MQL with nanofluid due to their rolling and sliding properties at grinding zone reduce the frictional coefficient and grinding forces thereby improving the surface finish of the workpiece than any other mode of lubrication.

Zhang et al. (2015c) compared performance of different lubricating oils (soybean oil, rapeseed oil, palm oil) in grinding 45 steel workpiece using $MoS_2$ (2 wt%) nanofluid-based MQL. Addition of $MoS_2$ in soybean oil enhanced viscosity which further improved lubrication properties of base fluid reducing grinding forces and grinding energy. Adding CNT, $MoS_2$ and $ZrO_2$ nanoparticles at different concentrations, each (1, 2, 3 wt%) (Zhang et al. 2015b) concluded that 2 vol% of CNT showed best cooling effect due to its higher conductivity than any other concentration of nanoparticles. Using same experimental conditions (Zhang et al. 2015a), compared grinding energy of $MoS_2$, CNT and $ZrO_2$ in colza oil as base fluid. $MoS_2$ with jet MQL recorded 32.7% J/mm$^3$ less specific grinding energy than that of CNT and $ZrO_2$.

Zhang et al. (2016) experimentally investigated the influence of nanofluids ($MoS_2$, CNT, $MoS_2$-CNT) with different concentrations (2, 4, 6, 8, 10, 12 vol%). Increasing the surface roughness resulted in increase in surface roughness value from 2% to 12%. Furthermore lowest G-ratio was observed with $MoS_2$-CNT which attributes to physical collaboration of both nanoparticles in lubrication mechanism.

Setti et al. (2015) analysed the influence of $Al_2O_3$ and CuO nanofluids on machining titanium alloy with MQL technique. Considerable reduction in coefficient of friction and cutting temperature was observed with water-based $Al_2O_3$ nanofluid than with CuO-based cutting fluid. Chip morphology also revealed about cooling and antiwear and self-cleaning lotus effect of nanoparticles.

Sinha et al. (2017) experimentally analysed the performance of nanofluids (Ag, ZnO) while machining Inconel 718 using considerably small amount of cutting fluid using SQL. Significant reduction in grinding forces, wear and small frictional coefficient was recorded with use of ZnO nanoparticle with improved surface finish on machined workpiece. This attributes to better lubricity and spreading ability of ZnO nanoparticles.

Wang et al. (2017b) compared the performance of $Al_2O_3$ at different concentrations (0.5–4 vol%) using MQL technique in grinding nickel-based alloy. Minimum contact angle (45°) for maximum lubricity and spreadability was observed at 2 vol%. Best tribological properties of nanofluid were obtained with 2 vol% of $Al_2O_3$; increase in concentration reduces the surface quality of workpiece. 24.3% reduction in force ratio and 34.1% reduction in grinding energy than pure MQL has been observed. Wang et al. (2017a) further added different nanoparticles ($MoS_2$, $SiO_2$, ND, CNT, $Al_2O_3$, $ZrO_2$) in palm oil as base fluid. $Al_2O_3$ provided best antifriction property by reducing frictional coefficient by 20% and w-ratio by 65%. Improved lubrication properties on addition of nanoparticles attribute to formation of tribofilm and polishing effect at wear zones and sliding surfaces. Li et al. (2017) using same setup and conditions as Wang et al. (2017a) experimentally analysed physical properties of different nanoparticles in grinding nickel alloy. Increase in concentration by volume of nanoparticles (up to 2 vol%) increases thermal heat transfer and viscosity of nanofluid. CNT with 2 vol% concentration records the lowest temperature (108°), and $SiO_2$ records lowest grinding force ratio. Furthermore lower contact angle will improve lubrication effect (Table 18.3).

### *18.4.3 MQL-Assisted Turning with Nanoparticles*

Krishna et al. (2010) experimentally studied the influence of mixing nanosolid suspensions of nanoboric acid in coconut oil and SAE-40 oil in machining AISI 1040. Turning operation was conducted on lathe with carbide inserts. It was recorded that flow rate of 10 ml/min and 0.5% concentration of nanoboric acid with coconut oil shows better performance in terms of heat transfer, tool wear and surface finish than nanoboric acid suspension in SAE-40 oil. With increase in concentration (up to 0.5 wt%) of nanoparticles, thermal conductivity increases, and due to reduced friction, there is a reduction in cutting temperature as well.

Yan et al. (2011) on mixing different concentrations of nanosolids $MoS_2$, Cu, CuO (1, 3, 5, 10, 20 wt%) and graphite fibre (0.2, 0.5, 1, 3, 5 wt%) in calcium-based greases in turning of RB-SiC ceramic, established that due to formation of thin tribolayer direct contact between tool and workpiece were significantly reduced. 10 wt% of copper nanoparticles in grease produces best surface finish and minimum tool wear which attributes to higher microplasticity of cu nanoparticles than others.

Khandekar et al. (2012) experimentally studied the effect of adding $Al_2O_3$ nanoparticles in turning AISI 4340 steel under dry, flood and nano-enriched servocut base fluid. Addition of 1% of $Al_2O_3$ enhances wettability of cutting fluid which enhances heat transfer property of cutting fluid. Enhanced heat dissipation and cooling characteristics of nano-enriched cutting fluid reduce cutting forces and tool wear during machining.

Amrita et al. (2013) experimentally investigated the influence of adding nanographite at different concentrations (0.1, 0.3, 0.5 wt%) in turning AISI 1040. Cutting fluid was supplied under different conditions of dry, flood and mist (5, 10, 15 ml/min) at different air pressures. With increase in pressure, droplet size of aerosol decreases which enhance lubrication and cooling property of cutting fluid. 15 ml/min and 0.5 wt% of $Al_2O_3$ decrease tool wear by 94.04% and 75.24% than dry and flood lubrication, respectively, for carbide tool. 71.92% reduction in tool wear was observed in case of HSS steel tool as compared to flood lubrication. Furthermore 76.25% and 56.98% reduction in cutting forces in case of carbide tool and 84.02% and 77.76% reduction in HSS steel was observed as compared to dry and flood machining.

Srikiran et al. (2014) investigated the influence of nanographite mixed cutting fluid in machining AISI 1040 steel using carbide insert. Cutting forces increase by

**Table 18.3** Literature review of MQL-assisted grinding with nanoparticles

| Author | Base fluid | Nanoparticle | Workpiece material | Parameters | | | Mode of nanofluid supply | Process findings |
|---|---|---|---|---|---|---|---|---|
| | | | | Cutting speed | Depth of cut | Feed rate | | |
| Shen et al. (2008b) | Deionized water, Cimtech 500 | $Al_2O_3$, ND (40, 100, 200 nm) | Dura-Bar 100-70-02 ductile iron | 30 m/s | 10 μm | 2400 mm/min | MQL | 2.5% of $Al_2O_3$ provided better surface finish than 1% or 4% concentration across and along grinding direction<br>Higher G-ratio was obtained by adding nanoparticles without any considerable change in grinding temperature |
| Shen et al. (2008a) | Paraffin oil<br>Soybean oil<br>CANMIST oil | $MoS_2$ (<100 nm) | Dura-Bar 100-70-02 ductile iron | 30 m/s | 10 μm | | MQL | 27% reduction in grinding forces was observed for CANMIST OIL, 21 for paraffin oil and 9% for soybean oil<br>Higher G-ratio for higher concentrations for $MoS_2$ was observed |
| Alberts et al. (2009) | IPA<br>TRIM SC200 | xGnP (5–10 nm) | D2 tool steel (62 HRC) | 25 m/s | 50 mm | 0.75 m/min | MQL | Larger size (15 μm) nanoparticles of graphite dispersed in IPA solution records reduction in specific energy, surface roughness and cutting forces |
| Kalita et al. (2010) | Soybean oil | $MoS_2$ | Dura-Bar 100-70-02 ductile iron | 30,000 mm/s | 2 mm | 40 mm/s | MQL | G-ratio improved without affecting the MRR<br>MQL accompanied with $MoS_2$ reduced the coefficient of friction thereby reducing tangential grinding forces |
| Prabhu and Vinayagam (2010) | SAE20W40 oil | MWCNT (10–20 nm) | AISI D2 tool steel | 2000 RPM<br>2500 RPM | 0.1 mm<br>0.2 mm | 1.9 mm/min<br>2.5 mm/min | MQL | Surface tribology improved from micro level to nano level by adding 2% of multiwall carbon nanotube (MWCNT) |
| Vasu and Kumar (2011) | TRIM E709 oil | $Al_2O_3$ (<100 nm) | EN-31 steel | 1400 RPM | 25 μm<br>50 μm<br>75 μm | 100 mm/s<br>150 mm/s<br>200 mm/s | MQL | Using TRIM E709 emulsifier, the cutting temperature reduced to 20–30% compared to plain emulsifier |

(continued)

**Table 18.3** (continued)

| Author | Base fluid | Nanoparticle | Workpiece material | Parameters | | | Mode of nanofluid supply | Process findings |
|---|---|---|---|---|---|---|---|---|
| | | | | Cutting speed | Depth of cut | Feed rate | | |
| Prabhu and Vinayagam (2012) | SAE20W40 oil | CNT (10–20 nm) | AISI D3 tool steel | 2000 RPM<br>2500 RPM | 0.1 μm<br>0.2 μm | 1.9 mm/min<br>2.5 mm/min | MQL | Addition of CNT increases the flash point and fire point of the base fluid by 6.3 and 5%<br>Surface finish was improved with the use of nanoparticles, from 0.54045 μm without to 0.4478 μm with CNT |
| Lee et al. (2012) | Paraffin oil | $Al_2O_3$<br>ND | SK-41C tool steel | 80,000 RPM | 5.0 μm | 120 mm/min | MQL | Size of nano-$Al_2O_3$ was recorded as critical parameter in reducing the surface roughness than ND<br>Small size and higher concentration of ND were more effective in reducing the grinding forces |
| Mao et al. (2012) | Deionized water | $Al_2O_3$ (40 nm) | AISI 52100 steel | 31.4 m/s | 10 μm | 0.05 m/s | MQL | Added nanoparticles of $Al_2O_3$ provide the ball-bearing effect which reduces the grinding forces, reduces the interface temperature and provides better lubricating conditions than water alone |
| Kalita et al. (2012a) | Paraffin oil<br>Soybean oil | $MoS_2$ (100 nm) | Dura-Bar 100-70-03<br>EN24 steel alloy | 30 m/s | 10 μm<br>20 μm | 0.06 m/s<br>0.1 m/s | MQL | Lowest frictional coefficient of 0.22 and 53% reduction in the energy consumption was observed in grinding with nanofluids<br>50% increase in G-ratio and increase in tool life were also observed with nMQL |
| Kalita et al. (2012b) | Soybean oil | $MoS_2$ (100 nm) | Dura-Bar 100-70-03 | 30 m/s | 10 μm<br>20 μm | 0.06 m/s | MQL | Formation of a tribo-chemical film on frictional surfaces reduces the friction, wheel wear and energy |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Mao et al. (2013b) | Deionized water | $Al_2O_3$ (60 nm) | AISI 52100 steel | 31.4 m/s | 10 μm | 0.05 m/s | MQL | Angular position of nozzle and increased air pressure results in enhanced grinding conditions with reduced cutting speed and surface roughness<br>Shorter spraying distance improves the grinding performance |
| Prabhu and Vinayagam (2013) | Water-soluble oil | SWCNT | Glass | 1200 m/min | 30 μm | 20 m/min | – | ELID technique with CNT nanoparticles tend to improve surface finish from (reduced from) 1.788 to 0.722 μm and microcracks |
| Mao et al. (2013a) | Deionized water | $Al_2O_3$ (40, 80, 70 nm) | AISI 52100 steel | 31.4 m/s | 10 μm | 0.05 m/s | MQL | Oil-based nanofluids have better surface finish and reduced cutting forces as compared to water-based nanofluids<br>Higher conc. of $Al_2O_3$ lowers the grinding temperature and grinding forces<br>Increase in diameter reduces the grinding forces but adversely affects the surface finish of workpiece |
| Mao et al. (2014b) | Deionized water | $Al_2O_3$ (10 nm) | – | – | – | – | MQL | It was concluded that the best dispersion property of $Al_2O_3$ was found when conc. is (0.5 wt%), pH value is 7 and ultrasonic vibration time is 1 h |
| Jia et al. (2014) | Soybean oil | $MoS_2$<br>$ZrO_2$<br>Polycrystal diamond (PCD)<br>$MoS_2$ | Hardened 45 steel | 30 m/s | 10 μm | 4 m/min | MQL | Anti-attrition effects of $MoS_2$ were observed the best<br>Both PCD and $ZrO_2$ provided the roller bearing characteristic at the sliding interface<br>Reduced grinding forces, friction coefficient and energy were achieved at 6% conc. by mass |

(continued)

**Table 18.3** (continued)

| Author | Base fluid | Nanoparticle | Workpiece material | Parameters | | | Mode of nanofluid supply | Process findings |
|---|---|---|---|---|---|---|---|---|
| | | | | Cutting speed | Depth of cut | Feed rate | | |
| Wang et al. (2014) | LB1000 | $MoS_2$ (50 nm) | Quenched 45 steel | 5–60 m/s | 10–45 μm | 0.01–0.1 m/s | MQL | Grinding temperature gets reduced by addition of nanoparticles, and there is elastic recovery of workpiece material due to effective cooling and lubrication |
| ManojKumar and Ghosh (2015) | Deionized water | MWCNT | Hardened AISI 52100 | 25 m/s | 10 μm<br>20 μm | 6 m/min<br>10 m/min | | 0.6 vol% of MWCNT proved better than soluble oil in reducing grinding forces<br>MWCNT nanofluid has potential to substitute synthetic oils in grinding hardened steel |
| Mao et al. (2014a) | Deionized water<br>Canola oil | $Al_2O_3$ (10 nm)<br>$MoS_2$ (70 nm) | AISI 52100 | 31.4 m/s | 10 μm | 0.05 m/s | MQL | 1.2 wt% of $Al_2O_3$ reduces grinding forces due to reduced coefficient of friction<br>Grinding temperature also reduces due to increase in convective heat transfer |
| Zhang et al. (2015c) | Liquid paraffin<br>Palm oil<br>Rapeseed oil<br>Soybean oil | $MoS_2$ (50 nm) | 45 steel | 30 m/s | 10 μm | 3 m/min | MQL | Optimum lubricating properties were achieved at 6% of $MoS_2$ in soybean oil<br>Soybean having low viscosity proved suitable for nanoparticles as base oil in jet MQL |
| Zhang et al. (2015b) | Soybean oil | $MoS_2$ (50 nm)<br>CNT<br>$ZrO_2$ | Hardened 45 steel | 35 m/s | 20 μm | 0.05 m/s | MQL | 2% volume conc. of CNT gave ideal experimental results with excellent cooling effects<br>$MoS_2$ with soybean as base fluid gave best lubrication results |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Setti et al. (2015) | Water | $Al_2O_3$<br>CuO | Ti-6Al-4V | 17 m/s | 5 μm | 9 m/min | MQL | Nanofluids enhance micron level grain fracture and reduce surface temperature, wear and friction between wheel and workpiece by forming a tribofilm |
| Zhang et al. (2015a) | Colza oil | $MoS_2$ (50 nm)<br>CNT<br>$ZrO_2$ | Hardened 45 steel | 35 m/s | 20 μm | 0.05 m/s | MQL | Lubrication performance and surface finish enhanced with 2 vol% of $MoS_2$ among all three |
| Prabhu et al. (2015) | SAE20W40 | MWCNT | AISI D3 tool steel | 2000 RPM<br>2500 RPM | 0.1 mm<br>0.2 mm | 1.9 m/s<br>2.5 m/s | MQL | Using ANOVA cutting speed was found significantly affecting surface roughness |
| Zhang et al. (2016) | Synthetic oil | $MoS_2$ (30 nm)<br>CNT<br>$MoS_2$-CNT | Ni-based alloy GH4169 440 C steel | 30 m/s | 10 μm | 3000 mm/min | MQL | Blend of $MoS_2$-CNT records the lower grinding ratio and surface roughness over $MoS_2$ and CNT used alone |
| Li et al. (2013) | Vegetable oil | CNT (50 nm) | 2Cr13 steel<br>45 steel<br>$ZrO_2$ | 40 m/s | 1 μm<br>5 μm<br>10 μm | 3 m/s | MQL | Better grinding performance can be achieved by 2 vol% of nanofluid due to improved tribological properties of CNT |
| Wang et al. (2017b) | Palm oil | $Al_2O_3$ (50 nm) | Nickel-based alloy GH4169 440C steel | 30 m/s | 10 μm | 3000 mm/min | MQL | The force ratio and specific grinding ratio lower down with use of nanofluids in MQL than pure MQL-based fluid 2.0 vol% of $Al_2O_3$ provides best tribological performance |
| Sinha et al. (2017) | Deionized water | Ag<br>Zno | Inconel 718 | 18 m/s | 10 μm | 6 m/min | | Nanofluid (Zno) girding minimizes the chance of redeposition of debris and oxide layer formation on ground machined surface<br>Due to better wettability and lubricity of nanofluids, no wear land was observed on the surface |

(continued)

**Table 18.3** (continued)

| Author | Base fluid | Nanoparticle | Workpiece material | Parameters | | | Mode of nanofluid supply | Process findings |
|---|---|---|---|---|---|---|---|---|
| | | | | Cutting speed | Depth of cut | Feed rate | | |
| Wang et al. (2017a) | Palm oil | $MoS_2$<br>CNTs<br>ND<br>$SiO_2$<br>Alpha-$Al_2O_3$ | Nickel-based alloy GH4169 440C steel | 30 m/s | 10 μm | 3000 mm/min | MQL | $Al_2O_3$ provide best surface morphology due to formation of thick tribofilm which reduces friction and wear<br>Nanofluids $MoS_2$, $SiO_2$ and $Al_2O_3$ provide better performance capabilities than base oil alone, and they are also termed as environmental-friendly nanofluids |
| Li et al. (2017) | Palm oil | $MoS_2$<br>CNTs<br>ND<br>$SiO_2$<br>Alpha-$Al_2O_3$ | Nickel-based alloy GH4169 440C steel | 30 m/s | 10 μm | 3000 mm/min | MQL | $SiO_2$ have lowest grinding force ratio with CNT having high conductivity |
| Pashmforoush and Bagherinia (2018) | Water | Cu | Inconel 738 | 20 m/s | 10 μm<br>20 μm<br>30 μm | 50 mm/s<br>100 mm/s<br>150 mm/s | | Surface roughness decreased by 59.19% using copper nanofluid, and adhesion of workpiece chips on wheel also reduced by 62.16% |

1.08 times when diameter of the nanographite decreased from (70–90 nm) to (5–10 nm) which attributes to increase in frictional resistance due to sliding and sticking phenomenon that increases cutting forces. Smaller size of nanoparticles results in increased surface roughness due to continuous rubbing, increase in temperature and tool chatter which degrades the surface quality of workpiece.

Chan et al. (2013) experimentally studied that surface properties and waviness of the workpiece can be enhanced by 19% and 22% with use of nano-droplet-enriched cutting fluid (NDCF). NDCF reduces the thrust forces by 26% and increases cutting to thrust force ratio reducing viscosity which can further improve surface roughness.

Saravanakumar et al. (2014) investigated the performance of silver nanoparticles-enriched cutting fluid in turning. It was experimentally observed that with addition of silver nanoparticles, there is reduction in cutting forces by 8.8% and surface roughness by 7.5% as compared to conventional fluids used for machining. Formation of a tribofilm with use of silver nanoparticles reduces the coefficient of friction and tends to increase tool life by bringing down the cutting temperature.

Amrita et al. (2014a) investigated different parameters in machining AISI1040 steel with uncoated carbide tool on addition of $nMoS_2$ (nano molybdenum sulphide), NBA (nanoboric acid) and FNG (functionalized nanographite). Addition of surfactant (SDBS) enhanced the stability of nanoparticles in base fluid. MQL technique with and without application of nanofluids provided better cutting performance than dry machining. $nMoS_2$-enriched cutting fluid significantly reduces surface roughness, wear and cutting forces compared to other nanofluids. NBA considerably reduces cutting temperature at the machining zone.

Sayuti et al. (2014b) designed his experiments using Taguchi method with different process parameters during turning of AISI 4140 hardened steel using $SiO_2$ nanoparticles. Using fuzzy logic and Taguchi analysis minimum surface roughness and tool wear was achieved by 0.5 wt% of $SiO_2$ at 30° and 60°, respectively. Increase in concentration degrades surface finish and increases tool wear.

Padmini et al. (2015) mixed $nMoS_2$ and boric acid ($H_3BO_3$) in sesame oil and coconut oil separately. The samples were then analysed under different lubricating conditions. Using MQL-based lubrication system with nano enrichment of both $MoS_2$ and boric acid, cutting forces and surface roughness were reduced up to 82% and 37% as compared to dry machining. $nMoS_2$ effectively reduces interface temperature of 37% and 31% in coconut and sesame oil, respectively.

Padmini et al. (2016) investigated influence of adding $nMoS_2$ in coconut, sesame and canola oil at different concentrations in turning of AISI 1040 steel. It was recorded that 0.5 wt% of $MoS_2$ effectively reduces cutting forces, surface roughness and tool wear by 37%, 39% and 44% as compared to dry machining. Furthermore $nMoS_2$ forms a fullerene-like nanofilm interface which results in reducing coefficient of friction.

Amrita et al. (2014b) investigated the influence of adding nanographite 0.3 wt% in water-soluble oil. AISI 1040 steel was turned using different lubrication techniques: dry, flood, pure fluid with MQL and nano-enriched cutting fluid, and results were compared experimentally. It was observed that mist application of nanofluid due to formation of fine aerosols enhances the cutting condition by bringing down interface temperature and reducing the tool wear. 54% reduction in cutting temperature, 25% in tool wear and 71% in surface roughness were observed as compared to flood lubrication.

Gupta et al. (2016) investigated influence of nMQL during turning in CNC machine using cubic boron nitride inserts. $Al_2O_3$, $MoS_2$ and graphite were mixed in vegetable oil for experimentation. After performing 29 experiments and optimization through ANOVA, it was recorded that cutting speed, cooling condition and feed rate contribute 40.20%, 36.50% and 20.13% and are significant parameters. Furthermore it was observed that graphite effectively reduce the cutting temperature as compared to other nanoparticles due to formation of lamellar structure between machining interfaces.

Su et al. (2016) investigated experimentally the performance of graphite-LB2000 and graphite-PriEco6000 nanofluids under different lubricating conditions. Experiments were conducted on turning AISI 1045 annealed carbon steel with uncoated carbide insert under dry, MQL and MQL with graphite-oil mixture. It was observed that MQL with graphite-enriched LB2000 nanofluid shows better performance than graphite-enriched PriEco6000 in terms of reduction in machining temperature and cutting forces.

Ali et al. (2017) studied influence of surfactant (SDBS w) in nano-enriched mixture of $Al_2O_3$ and soluble oil at different concentrations (0.1, 0.4, 0.6 wt%). Increasing the concentration of nanoparticles surface roughness of the workpiece reduces. Feed rate was calculated as most significant factor using ANOVA analysis.

Raju et al. (2017) investigated the performance of MWCNT (2 vol%) with distilled water. Machining with MWCNT reduces tool wear by 40% and cutting forces by 5–8% in comparison with base fluid and dry machining, respectively. Furthermore presence of nanoparticles reduced the contact angle by 33.33% as compared to conventional fluid which enhances the wear resistance capability of cutting fluid.

Behera et al. (2017) experimentally compared the spreading coefficient of different surfactants (CTAB, SDS, Tween-20, PVP) on cutting tool surface. Reduction in tangential force (29.72%), coefficient of friction (7.25%) and feed force (19.39%) were observed with Tween-20-NF compared to dry and other surfactant-rich nanomachining. Reduction of about 33.35% in chip tool interface was observed with Tween-20 NF compared to dry environment.

Hegab et al. (2018b) experimentally observed the performance of MWCNT-rich nanofluid on turning titanium alloy by varying cutting speeds. Using ANOVA analysis it was recorded that MWCNT-rich nanofluid gave better results in power consumption and flank wear than base fluid alone. Significant improvement on cutting temperature, cooling and wetting characteristics of base fluid was observed by using MWCNT. Continuing their work Hegab et al. (2018a) studied the effect of turning with nano-enriched cutting fluid on chip morphology and tool wear on machining Inconel 718. MWCNT and $Al_2O_3$ have been used to enhance the lubrication properties of base fluid. Less deformation in chip and enhancement in interface bonding of tool and chip were observed which attributes to increase in shear angle and superior cooling characteristics of cutting fluid.

Sartori et al. (2018) observed the cooling and lubrication characteristics of solid lubricants (graphite and PTFE) using MQL technique on turning Ti-6Al-4V alloy. Reduction in crater and nose wear was observed due to improved dynamic viscosity of solid lubricant-assisted MQL-MQC (Table 18.4).

### *18.4.4 MQL-Assisted Milling with Nanoparticles*

Park et al. (2011) experimentally analysed the effect of nano-enhanced lubrication in ball milling AISI 1045 steel workpiece using MQL technique. Nanographene (xGnP) particles were mixed with vegetable oil, and experiment was conducted in vertical milling machine under dry, flood, water-soluble mineral oil, units cooltube 200 (vegetable oil) and xGnP nanoparticle in vegetable oil with MQL. 0.1 wt% and 1 μm diameter are regarded as optimum concentration and size of nanoparticle for enhanced cutting performance as compared to 1 wt% and 15 μm. The layered structure of nanographene reduces coefficient of friction significantly.

Sarhan et al. (2012) investigated the effect of $SiO_2$ nano-enriched milling of AA6061-T6 alloy using MQL. It was observed that $SiO_2$ mixed with mineral oil improved milling performance in terms of specific power, cutting forces and coefficient of friction as compared to base fluid alone which attributes to sliding and rolling action of nano $SiO_2$. Using same setup (Sayuti et al. 2013a) studied the effect of concentration, nozzle angle and cutting temperature. Using ANOVA analysis minimum cutting force was observed with 0.2 wt% $SiO_2$ and 60° nozzle angle, and minimum cutting temperature was observed with 15° nozzle angle at 2 bar air pressure. Surface roughness can be minimized with high concentration of nanoparticles and with 30° nozzle angle.

Sayuti et al. (2013b) studied the influence of carbon anion-enriched nanofluid on machining aerospace aluminium alloy (duralumin Al-2017-T4) using vertical milling machine. 0%, 0.5%, 1% and 1.5 wt% concentrations of carbon anion were used during machining, and it was observed that 21.99% and 46.32% reduction in cutting forces and surface roughness can be obtained by nano-enriched cutting fluid as compared to conventional oil lubrication. Higher concentration of nanoparticles reduced cutting forces and improved surface quality. Sayuti et al. (2014a) concluded that addition of $SiO_2$ improves the surface morphology during milling and reduces the thermal deformation of workpiece which attributes to the rolling action and formation of thin tribofilm that improves surface quality and conductivity.

Rahmati et al. (2014) analysed the milling performance on aluminium alloy and recorded improvement in surface finish by 3.87% with 0.5 wt% $MoS_2$-enriched cutting fluid as compared to conventional oil. With further increase in concentration of nanoparticles, surface finish deteriorates. FESEM and XRD were used to study surface morphology.

Najiha et al. (2015) analysed the performance of water-mixed nanoparticles ($TiO_2$) and compared the results with that of conventional oil-mixed nanoparticles. It was observed that both techniques produce almost same results for tool wear,

**Table 18.4** Literature review of MQL-assisted turning with nanoparticles

| Author | Base fluid | Nanoparticles | Workpiece material | Parameters | | | Mode of lubrication | Process findings |
|---|---|---|---|---|---|---|---|---|
| | | | | Cutting speed | Depth of cut | Feed rate | | |
| Krishna et al. (2010) | Coconut oil, SAE-40 | Nanoboric acid (50 nm) | AISI 1040 steel | 60, 80, 100 m/min | 0.1 mm | 0.14, 0.1, 0.2 mm/rev | MQL | Percentage increase in conc. of nanoboric acid increases the thermal conductivity and decreases specific heat<br>0.5% of nanoboric acid reduces cutting temperature and improves tool life and surface finish |
| Yan et al. (2011) | Calcium-based grease | $MoS_2$<br>GF<br>Cu<br>CuO | RB-Sic | 1000 RPM | 2 µm | 20 mm/min | MQL | Best surface quality and less tool wear were obtained at 10 wt% cu conc. in grease |
| Khandekar et al. (2012) | Servocut S | $Al_2O_3$ | AISI 4340 | 350 m/min | 0.1 mm | 0.1 mm/rev | MQL | Addition of 1% of $Al_2O_3$ in base fluid enhances the wettability of base fluid<br>50% reduction in cutting forces by using nanofluids as compared to dry machining<br>54.4% reduction in surface roughness when nanofluid is used |
| Amrita et al. (2013) | – | Nanographite (<80 nm) | AISI 1040 | 40.7 m/min | 1 mm | 0.14 mm/rev | MQL | Min tool wear, tool chip interface temperature and cutting forces were observed for 15 ml/min flow rate and 0.5 wt% of nanoparticles |
| Amrita et al. (2014b) | Conventional water (nano-SO) | Nanographite (<80 mm) 10 ml/min | AISI1040 | 40 m/min | – | 0.14 mm/rev | MQL | 70%, 25% and 20% reduction in cutting temperature was observed with nanofluid cutting than dry, flood and mist fluid applications<br>Surface roughness reduced by 42%, 32% and 28%, respectively |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Srikiran et al. (2014) | SAE-40 oil | Nanographite<br>(5–10 nm)<br>(15–30 nm)<br>(40–60 nm)<br>(70–90 nm) | AISI 1040 | 51 m/min<br>78 m/min<br>126 m/min<br>192.6 m/min | 0.25 mm<br>0.50 mm<br>0.75 mm<br>1.0 mm | 0.05 mm/rev<br>0.08 mm/rev<br>0.10 mm/rev<br>0.125 mm/rev | MQL | Cutting forces, frictional forces and tool interface temperature increase due to decrease in size of nanoparticles from 70–90 nm to 5–10 nm |
| Chan et al. (2013) | JAEGER SW-105 oil | – | 6061-T651 brass<br>Pure copper | 2000 RPM<br>8000 RPM | 30 μm<br>20 μm | 30 mm/min<br>20 mm/min | – | Reduced roughness and enhanced waviness were observed by using cutting fluid with nano-droplet-enriched cutting fluid (NDCF) |
| Saravana-kumar et al. (2014) | Distilled water | Ag | – | 50.4 m/min<br>64.8 m/min | 3 mm<br>5 mm | 0.1 mm/rev<br>0.2 mm/rev | MQL | Surface roughness decreased by 7.5% with use of nanoparticles<br>Rate of heat transfer at chip tool interface improved with decrease in cutting forces by 8.8% |
| Amrita et al. (2014a) | Water-based soluble oil | FNG (80 nm)<br>NBA (100)<br>nMoS$_2$ (100) | AISI 1040 | 65 m/min | 0.75 mm | 0.14 mm/rev | MQL | MoS$_2$ (0.3 wt%) recorded better surface properties with lower wear and reduced cutting forces |
| Sayuti et al. (2014b) | Mineral oil | SiO$_2$ (5–15 nm) | AISI 4140 | 0.15 mm/rev | 0.5 mm | 0.15 mm/rev | MQL | Minimum tool wear was obtained with 0.5% conc. of nanoparticles and 2 bar pressure in mineral oil with 60° nozzle angle and improved surface roughness at 30° angle of nozzle |
| Padmini et al. (2015) | Coconut oil (CC), sesame oil (SS) | Boric acid<br>MoS$_2$ (<100 nm) | AISI 1040 (30 HRC) | 60 m/min | 0.5 mm | 0.14 mm/rev | MQL | As compared to dry machining, nMoS$_2$ with coconut and sesame oil reduces surface roughness by 46%<br>nMoS$_2$ effectively reduced tool wear by 28% and 38% in coconut and sesame oil |

(continued)

**Table 18.4** (continued)

| Author | Base fluid | Nanoparticles | Workpiece material | Parameters | | | Mode of lubrication | Process findings |
|---|---|---|---|---|---|---|---|---|
| | | | | Cutting speed | Depth of cut | Feed rate | | |
| Padmini et al. (2016) | Coconut oil (CC)<br>Sesame oil (SS)<br>Canola oil (CAN) | Boric acid<br>$MoS_2$ (<100 nm) | AISI 1040 | 40 m/min<br>60 m/min<br>100 m/min | 0.5 mm | 0.14 mm/rev<br>0.17 mm/rev<br>0.20 mm/rev | MQL | 5% coconut oil and $nMoS_2$ reduces cutting forces by 37%, cutting temperature by 24% and tool wear by 44% than any other nanofluid |
| Gupta et al. (2016) | Vegetable oil | $Al_2O_3$ (<50 nm)<br>$MoS_2$<br>Graphite | Titanium (grade 2) | 215 m/min<br>250 m/min | 1 mm | 0.10 mm/rev<br>0.15 mm/rev | MQL | Lower cutting temperature and cutting forces were observed using graphite-based nanofluids |
| Su et al. (2016) | LB2000<br>PriEco6000 | Graphite | AISI 1045 | 55 m/min<br>96 mm/min | 1 mm | 0.10 mm/rev | MQL | Using nanofluids cutting forces and temperature reduced 11.9% and 21% with respect to dry machining |
| Ali et al. (2017) | SolCut | $Al_2O_3$ (<50 nm) | Ti-6Al-4V | 75 m/min<br>85 m/min<br>95 m/min | 1 mm | 0.10 mm/rev<br>0.15 mm/rev<br>0.20 mm/rev | MQL | Taguchi method was applied to find set of combinations of parameters for producing optimum surface roughness, tool wear and power consumption |
| Raju et al. (2017) | Distilled water | MWCNT | EN31 | 1500 RPM | 1 mm | 0.1 mm/rev | – | Tool wear improved by 49% using MWCNT nanofluid as compared to dry machining, and 30% reduction was observed than conventional fluid<br>9–12% reduction in surface roughness and cutting forces reduce by 5–8% with use of MWCNT-enriched nanofluid over conventional fluid |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Behera et al. (2017) | Deionized water | $Al_2O_3$ | Inconel 718 | 60 m/min<br>80 m/min | 0.5 mm | 0.2 mm/rev | MQL | Reduction in chip curling, cutting forces and coefficient of friction was observed as a result of good spreading behaviour of nanofluids |
| Hegab et al. (2018b) | – | MWCNT<br>$Al_2O_3$ | INCONEL 718 | 40 m/min<br>50 m/min<br>60 m/min | – | 0.2 mm/rev<br>0.3 mm/rev<br>0.4 mm/rev | MQL | Addition of MWCNT and $Al_2O_3$ reduces cutting forces due to increase in shear angle and adequate dissipation of heat |
| Hegab et al. (2018a) | ECOLUBRIC E200 | MWCNT | Ti-6Al-4V | 120 m/min<br>170 m/min<br>220 m/min | – | 0.1 mm/rev<br>0.15 mm/rev<br>0.2 mm/rev | MQL | 2 wt% of nanoparticles in base solution provides better cutting performance at less power consumption than 4 wt% of nanofluid |
| Sartori et al. (2018) | AstroCut HD XBP | PTFE (polytetrafluoroethylene) (5 μm)<br>Graphite | Ti-6Al-4V | 80 m/min | 0.25 mm | 0.2 mm/rev | MQL<br>MQC | Addition of PTFE assisted the cratering phenomenon, and tool wear reduced with less abrasion of cutting edge |
| Sharma et al. (2018) | Alumina | Graphene | AISI 304 steel | 60 m/min<br>90 m/min<br>120 m/min | 0.6 mm<br>0.9 mm<br>1.2 mm | 0.08 mm/rev<br>0.12 mm/rev<br>0.16 mm/rev | MQL | Addition of graphene in alumina increases its wettability<br>1.25 vol% of alumina and Al-GnP hybrid nanofluid shows lowest coefficient of friction and wear |

but edge chipping is reduced in water-based MQL due to higher cooling rate and higher concentration of aluminium in deposited layer on flank face. Using same setup (Najiha and Rahman 2016) compared the wear phenomenon for $TiO_2$-enriched water and conventional oil using MQL technique. Adhesion and abrasion wear were found to be major tool wear phenomenon in all three cases of lubrication (flood, MQL with vegetable oil, and MQL with water) which were comparable in all three modes of lubrication. Furthermore it was observed that due to cooling effect and high latent heat produced by water-based MQL, edge fracture and edge chipping were not seen. Varying concentrations of nanoparticles (0.5, 2.5, 4.5 wt%) of $TiO_2$ in same setup (Najiha et al. 2016) recorded minimum tool wear at 2.5 vol% compared to other lubricating conditions. Experimental results were then compared with those of three-level fuzzy logic system.

Kim et al. (2016) compared four different lubrication techniques (dry, flood, MQL with hBN in vegetable oil with and without chilly $CO_2$ gas in end milling of Ti-6Al-4V alloy). 0.1 wt% of hBN provided enhanced milling performance than other lubrication techniques. Cooling and lubrication effect of both chilly $CO_2$ gas and hBN effectively reduce surface roughness, chip adhesion of machined surface and tool wear.

Muthusamy et al. (2016) analysed the wear analysis on milling of AISI 304 with $TiO_2$ mixed ethylene glycol nanofluid with different concentrations (0.5, 1.0, 1.5 vol%). Milling AISI 304 steel with tin-coated carbide tool using $TiO_2$ mixed nanofluid increase tool life (54.9 min) as compared to water-soluble coolant (32.67 min). Enhanced tool life was obtained with 1 vol% of $TiO_2$ at all cutting speeds. It was observed from results shown by EDX and ESM that a layer formation by embedment of nanoparticles from nanofluid acts as a protective layer for cutting tool.

Lv et al. (2018) studied the effect of hybrid nanoparticles graphene dioxide and silicon dioxide (GO and $SiO_2$) in water-based MQL lubrication technique at varying concentrations of both. On end milling of AISI 304, it was observed that addition of 0.02:0.05% of GO:$SiO_2$ in water resulted in reduced tool wear, with improved surface finish and tool life. $SiO_2$ and GO nanoparticles penetrate into the pits of the friction region thereby forming a smooth surface which enhances the rolling effect of $SiO_2$ and slipping of GO sheets thereby forming a thin protective layer which distributes stress concentration and separates the sliding pairs minimizing wear (Table 18.5).

## 18.5 Future Scope

Previous researchers have focused more on lubricants containing single type nanoparticles in mineral oils preferably. In the above study, the authors have tried to experimentally investigate the blending of two different types of nanoparticles having two different properties and mechanisms they involve in. The blending of grapheme (GnP) with $TiO_2$ (titanium dioxide) in a fixed ratio (1:1) along with a biodegradable oil improved tribological and thermophysical properties of the oil for

**Table 18.5** Literature review of MQL-assisted milling with nanoparticles

| Author/year | Base fluid | Nanoparticles | Workpiece material | Parameters | | | Mode of lubrication | Process findings |
|---|---|---|---|---|---|---|---|---|
| | | | | Cutting speed/wheel speed | Depth of cut | Feed rate/ workpiece speed | | |
| Park et al. (2011) | Vegetable oil | xGnP (1 μm) | AISI 1045 | 3500 RPM<br>4000 RPM | 1.0 mm<br>0.6 mm | 2500 mm/ min | MQL | Addition of xGnP nanoparticles increases wettability and reduces friction<br>0.1 wt% of xGnP resulted in improved cutting performance without agglomeration |
| Sarhan et al. (2012) | ECOCUT SSN 322 mineral oil | $SiO_2$ (5–15 nm) | Aluminium alloy AA6061-T6 | 500 RPM | 5 mm | 100 mm/ min | MQL | $SiO_2$ nanoparticles reduce contact friction due to which there is less consumption of specific energy and power |
| Sayuti et al. (2013a) | ECOCUT SSN 322 | $SiO_2$ (5–15 nm) | Aluminium alloy AA6061-T6 | 5000 RPM | 5 mm | 100 mm/ min | MQL | Minimum cutting force can be observed at 0.2 wt% of $SiO_2$, and minimum cutting temperature was observed at 15° nozzle orientation angle |
| Sayuti et al. (2013b) | Alumicut oil | Carbon anions (5–20 nm) | Duralumin AL-2017-T4 | 75.408 m/ min | 1.0 mm | 100 mm/ min | MQL | Best surface topography and reduced cutting forces were observed at 1.5 wt% conc. of carbon anions<br>Rolling action of nanoparticles reduces cutting forces and surface finish by 21.995 and 46.32% |
| Sayuti et al. (2014a) | ECOCUT SSN 322 | $SiO_2$ | Aluminium alloy AA6061-T6 | 5000 RPM | 5.0 mm | 100 mm/ min | MQL | Addition of $SiO_2$ improved the surface morphology with formation of thin tribofilm thereby reducing frictional wear and thermal deformation during machining |

(continued)

**Table 18.5** (continued)

| Author/year | Base fluid | Nanoparticles | Workpiece material | Parameters |  |  | Mode of lubrication | Process findings |
|---|---|---|---|---|---|---|---|---|
|  |  |  |  | Cutting speed/wheel speed | Depth of cut | Feed rate/ workpiece speed |  |  |
| Rahmati et al. (2014) | ECOCUT HSG 905S oil | $MoS_2$ (20–60 nm) | Aluminium alloy AA6061-T6 | 8000 RPM | 5 mm | 2100 mm/ min | MQL | 0.5 wt% of $MoS_2$ improved the surface quality than 1 wt% of $MoS_2$ |
| Najiha et al. (2015) | Deionized water | $TiO_2$ (40 nm) | Aluminium alloy AA6061-T6 | 5300 RPM<br>5500 RPM | 3 mm | 440 mm/ min | MQL | Higher cooling rates with reduced chipping of tool were observed with addition of $TiO_2$ in deionized water |
| Najiha and Rahman (2016) | Deionized water | $TiO_2$ (40 nm) | Aluminium alloy AA6061-T6 | 5300 RPM<br>5500 RPM | 3 mm | 440 mm/ min | MQL | 2.5 vol% reduces BUE formation and reduces chipping of tool material with improved cooling conditions |
| Kim et al. (2016) | Vegetable oil | (hBN) hexagonal boron nitride | Titanium alloy Ti-6Al-4V (70 nm) | 45,000 RPM | 100 μm | 5 μm/tooth | MQL | Chilling effect of $CO_2$ reduces cutting forces, tool wear and improved surface finish<br>Micro-end-milling performance improved by adding 0.1 wt% of hBN |
| Muthusamy et al. (2016) | Ethylene glycol | $TiO_2$ | AISI 304 steel | 1500 RPM<br>2500 RPM | 0.1 mm<br>0.3 mm | 0.02 mm/ tooth<br>0.04 mm/ tooth | MQL | Tool life increased by 40.55% with addition of $TiO_2$ in base fluid |
| Park et al. (2017) | Vegetable oil | xGnPs | Ti-6Al-4V | 46.5 m/min<br>76.4 m/min<br>100 m/min<br>120 m/min | 2 mm | 0.15 mm/ rev | MQL, cryogenic cooling | Addition of nanoparticles reduces tool wear and friction at higher cutting speed even when base fluid vaporize at high surface temperature |
| Lv et al. (2018) | Water PEG solution | GO (5–10 nm)<br>$SiO_2$ (5–10 nm) | AISI-304 | 100 m/min | 1 mm | 0.12 mm/ tooth | MQL | 0.02 wt% of GO and 0.50 wt% of $SiO_2$ in base fluid reduce tool wear and improve surface roughness due to their ball-bearing effect |

manufacturing operations. The nanofluid was then experimentally tied for turning operation on a commercial lathe machine with minimum quantity lubrication technique to minimize the usage of the prepared nanofluid providing cost benefits.

1. The present work can further be extended to discover environment-friendly vegetable oils that have the potential to be used as cutting fluids in common manufacturing operations.
2. Suitable additives in the form of nanoparticles with different weight fractions, shapes and sizes can be used to enhance the thermophysical properties of cutting oils. This would be helpful in developing nano-lubricants with enhanced tribological properties for the machining of specific metals and alloys.
3. Moreover, the present work can further be extended to the optimization of nanoparticle volume fraction, their shape and their size. This would be helpful in developing nano-lubricants with improved tribological properties for the machining of specific metals and alloys.
4. Different tool and workpiece combinations can be checked for optimum tool life and economic analysis.

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