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Thermodynamic Mechanism of Nanofluid Minimum Quantity Lubrication Cooling Grinding and Temperature Field Models

Min Yang, Changhe Li, Yanbin Zhang, Dongzhou Jia, Runze Li and Wenfeng Ding

Abstract

Grinding is an indispensable form of machining, in which, a large amount of heat is transferred into workpiece surface, causing surface burn of the workpiece. Flood grinding is easy to cause pollution to the environment while dry grinding and minimum quantity lubrication (MQL) is insufficient of cooling and lubrication effect. The appearance of nanofluid minimum quantity lubrication cooling (NMQLC) technique can effectively solve the problem of heat transfer in grinding zone and also enhance the lubrication characteristics. In this chapter, NMQLC technique, including nanofluid preparation and atomization is summarized first; then a review on the mechanism of grinding thermodynamics under NMQLC condition is presented based on published literatures. Most of the studies, including investigation of grinding forces and temperatures, indicate that NMQLC has realized a lubrication-cooling effect close to that of flood lubrication. According to existing investigations, theoretical models of temperature field are concluded, heat source distribution model, thermal distribution coefficient model, and heat transfer coefficient model under NMQLC condition are developed, and temperature field control equation are determined. This chapter reviews and amasses the current state of the mechanism of grinding thermodynamics and also recommends ways to precision control the grinding temperature field.

Keywords: nanofluid, minimum quantity lubrication, grinding, thermodynamics mechanism, temperature field, thermal models

1. Introduction

The most significant features of grinding process are high grinding wheel speed and high energy consumption. As abrasive grains on grinding wheel surface in grinding process are usually cut at negative rake, the energy consumed for grinding process to remove unit volume of materials is far greater than other machining forms and most of the energy will be converted into heat quantity [1, 2]. And more than 90% of the heat quantity will be transferred inside grinding wheel and workpiece, reducing the life of the grinding wheel and surface quality of the workpiece [3–5].

Cooling and lubrication grinding processing method applied to industrial production at the earliest is flood grinding, namely, injecting a large quantity of grinding fluid in grinding zone in the form of continuous fluid supply. However, the application of a large amount of grinding fluids results in high cost, and moreover, "air barrier" phenomenon generated surrounding the grinding wheel, preventing grinding fluids from entering the wedge-shaped zone between grinding wheel and workpiece [6–8].

As a kind of green and environmentally friendly processing technology appearing at the earliest, dry processing technology has abolished the application of cutting fluids on the precondition that machining precision and tool service life are guaranteed. However, it is difficult for heat quantity generated during the dry grinding process to be taken away by debris and the main heat quantity will still be transferred into grinding wheel and workpiece.

Minimum quantity lubrication (MQL) grinding processing technology is another green machining technology [9–11]. It refers to a grinding processing technology in which minimum quantity lubricant is mixed and atomized with gases under a certain pressure and then sprayed into grinding zone so as to exert cooling and lubricating effects. However, study shows that heat quantity generated by the grinding process and brought away by high-pressure gases are quite limited [12–14].

In view of flood grinding and cooling properties of MQL, researchers have been anxious to seek for a new cooling and lubricating form to apply to the grinding process. Relevant theories about heat transfer enhancement show that the heat transfer capability of solid is greater than that of liquid and gas [15–17]. On this basis, researchers have put forward nanofluid minimum quantity lubrication cooling (NMQLC) technique which adds a certain amount of nanoscale solid particles into degradable minimum quantity lubricant to generate nanofluids, and then nanofluids will be atomized through high-pressure gas and transferred into grinding zone in way of jet flow [18–22]. Sheikholeslami [23, 24] simulated the natural convection of water-based CuO nanofluid considering Brownian motion. Results showed that the Nusselt number decreases with the increase of Hartmann number and increases with the increase of volume fraction and Rayleigh number of nanofluids. NMQLC grinding process has integrated all advantages of MQL grinding process, solved heat transfer problems of MQL grinding, significantly improved workpiece surface quality and burning phenomenon, lengthened service life of grinding wheel and improved working environment. Therefore, it is a green and environmentally friendly, high-efficiency, and low-energy-consumption grinding processing technology [25, 26].

In this chapter, nanofluid preparation and atomization technique are concluded. A review on the mechanism of grinding thermodynamics under NMQLC condition is presented based on published literatures. According to existing investigations, theoretical models of temperature field precision control are obtained. This chapter reviews the current state of the mechanism of grinding thermodynamics and recommends ways to precision control the grinding temperature field.

2. Nanofluid minimum quantity lubrication cooling technique

2.1. Preparation of nanofluids

Preparation of nanofluids is the precondition for NMQLC grinding and high-quality nanofluids can obtain favorable cooling and lubricating effects. Nowadays, preparation method of nanofluids can be divided into two types: single-step method and two-step method. Single-step nanofluid preparation method is to disperse nanoparticles in base fluid while preparing them, which then saves the problems like nanoparticle collection and storage and can effectively avoid the oxidizing reaction of metal nanoparticles in atmosphere. This method is of high cost and small preparation quantity, and it is not suitable for actual batch application in production [6].

Two-step nanofluid preparation method is to add a certain proportion of nanoparticles in base fluid and select corresponding surface dispersant together with supersonic vibration according to physical and chemical properties so that nanoparticles can be distributed uniformly and stably in base fluid and nanofluid with suspension stability will be formed [27]. The two-step nanofluid preparation method is of simple operation and extensive application and it is nearly applicable to the preparation of all kinds of nanofluids.

2.2. Atomization of nanofluids

When nanofluids are applied to NMQLC grinding, studies on their atomization modes are mainly divided into three types: pneumatic atomization, electrostatic atomization, and ultrasonic atomization.

Pneumatic atomization is a process in which the liquid is sprayed in the machining region after small liquid drops are formed through high-pressure gas atomization and it is the most commonly used method for the atomization of nanofluids. Influenced by external forces like aerodynamic force, the liquid will be split while surface tension of the liquid will make the liquid form spherical liquid drops which are also influenced by viscosity. When external force born by the liquid is greater than liquid surface tension and viscous resistance, force balance of the liquid will be broken and the liquid will be split into fine liquid drops which will form nanofluid drop shapes when they are small enough [28].

Besides high-pressure gases are used for atomization of nanofluids, researchers have also put forward electrostatic atomization and ultrasonic atomization. The formers refer to atomizing

the liquid drops under electric charge through high-voltage electrostatic field after nanofluids are sprayed out from the nozzle so as to form electrically charged liquid drop flocks, which will be controllably and orderly transported onto workpiece surface under the effect of electric field force. For ultrasonic atomization, micro shock waves are generated during ultrasonic cavitation and bubble closing process in the liquid to damage the interaction between liquid molecules and then liquid particles are dragged out from liquid surface to form liquid drops [29].

3. A review on the law of grinding thermodynamics

3.1. A review on grinding forces under NMQLC condition

More research has been done on the lubrication effect of the NMQLC technique based on published literatures. A good lubrication in the grinding zone can reduce the grinding wheel/workpiece friction, thereby reducing grinding force and heat generation [30–32]. Manojkumar and Ghosh [33] found that nanofluid could substantially outperform soluble oil in terms of grinding force and G ratio (representing wheel life) under NMQLC. Setti et al. [34] showed that NMQLC could reduce normal force (F_n) on an average of 12 and 28% and reduce F_t on an average of 15 and 27% compared to flood and MQL. Sinha et al. [35] reported that grinding forces, coefficient of friction (μ) can be reduced to the maximum by nanofluids. Kalita et al. [36] measured a decline of 45–50% in force-ratio against grinding with flood cooling and MQL. Shen et al. [37] showed that lubricants with MoS_2 nanoparticles significantly reduce the F_t and the overall grinding performance. Jia et al. [38] found that soybean/castor mixed oil obtained the optimal results and lubricating effect compared to castor oil and other mixed base oils. Zhang et al. [39] reported that the energy ratio coefficient of flood lubrication, MQL, and NMQLC was 36.8, 52.1, and 41.4%, respectively, indicating that NMQLC realized a lubrication cooling effect close to that of flood lubrication. Zhang et al. [40, 41] found that NMQLC grinding using mixed nanoparticles obtain lower grinding force ratios and surface roughness (R_a) values, showing that mixed nanoparticles is superior to pure nanoparticles. Lee et al. [42, 43] carried out micro scale grinding experiments under different lubrication conditions and experimental results demonstrated that NMQLC could significantly reduce the grinding forces and enhance the surface quality. Yang et al. [44] investigated the critical maximum undeformed equivalent chip thickness for ductile-brittle transition (DBh_{max-e}) of zirconia ceramics under different lubrication conditions and found that lubrication condition affects the normal force and ultimately influences the resultant force on workpiece, making DBh_{max-e} decreases with increasing friction coefficient.

Figure 1(a) and **(b)** show the specific tangential grinding force and μ under dry, flood, MQL, and NMQLC conditions in the investigation of Jia et al. [6]. The maximum specific tangential grinding force and μ were obtained in dry grinding. Compared with dry grinding, the specific F_t under MQL, NMQLC, and flood conditions decreased successively by 45.88, 62.34, and 69.33%, respectively. Therefore, flood grinding realized the optimal lubrication effect, followed by NMQLC. It can also be seen from **Figure 1** that the specific tangential grinding force and μ, which NMQLC realized a lubrication cooling effect close to that of flood lubrication.
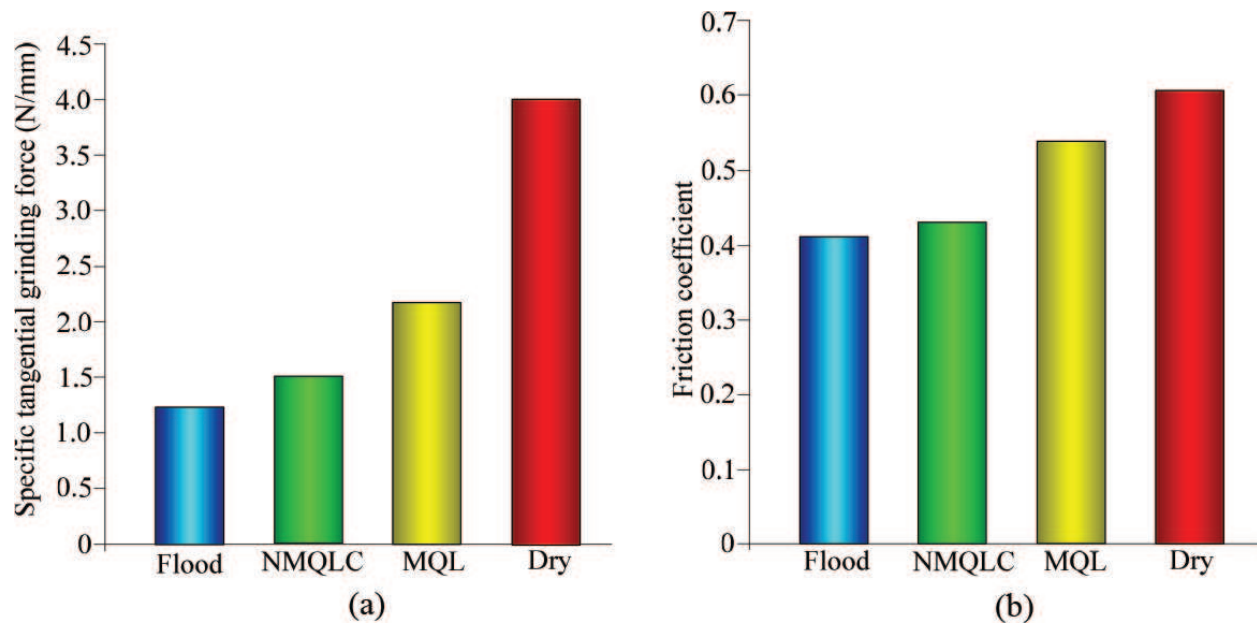
Figure 1. Specific tangential grinding force and frictional coefficient under different lubricating conditions [6]. (a) Specific tangential grinding force. (b) Frictional coefficient.

Table 1 summarizes the details of investigations on nanofluid parameters for the application of NMQLC technique in improving lubrication.

3.2. A review on grinding temperature under NMQLC condition

NMQLC technique was first proposed to solve the problem of inadequate cooling of MQL in grinding [45–48]. Grinding temperature is usually measured by thermocouples. The thermocouples can be placed on the workpiece or on the surface of the grinding wheel. As shown in **Figure 2** [49], a thermocouple forms a junction when the grinding wheel passes over the exposed single pole. The pole is smeared onto the workpiece, thereby forming a junction with the ground surface.

Mao et al. [50] analyzed the effect of nanofluid parameters on grinding performance. It is found that the cooling performance in the grinding zone is improved with the increase of the nanoparticle concentration and nanoparticle diameter. Yang et al. [51] studied the effect of different nanoparticles and concentrations on the temperature field of micro grinding. It was found that different thermal physical properties of nanoparticles have different effects on the temperature field. Yang et al. [52] investigated the dynamic heat flux in micro grinding using different sizes of Al_2O_3 nanoparticles. Results showed that temperatures under NMQLC using nanofluids (30, 50, 70, and 90 nm) are 21.4, 17.6, 16.1, and 8.3% lower, respectively. Li et al. [53] studied the grinding temperature using six types of nanoparticles (MoS_2, ZrO_2, CNT, polycrystalline diamond, Al_2O_3, and SiO_2), and found that CNT nanofluid results in the lowest grinding temperature of 110.7°C with the associated energy proportionality coefficient of 40.1% and the highest heat transfer coefficient of 1.3×10^4 W/(m K).

Authors	Nanoparticle	Particle size (nm)	Base fluid	Concentration
Manojkumar and Ghosh [33]	MWCNT	Not mentioned	Deionized water, soluble oil	0.6, 1 vol.%
Setti et al. [34]	Al_2O_3	40	Water	1 vol.%
Sinha et al. [35]	Ag, ZnO	10 (Ag), 25 (ZnO)	Deionized water	10~30 vol.% (Ag), 0.01~0.5 vol.% (ZnO)
Kalita et al. [36]	MoS_2	70 nm along major axis and 40 nm along minor axis	Paraffin oil	2, 8 wt.%
Shen et al. [37]	MoS_2	70 nm along major axis and 40 nm along minor axis	Paraffin oil, CANMIST oil, soybean oil	5, 20 wt.%
Jia et al. [38]	MoS_2	50	Castor, palm, soybean, peanut, rapeseed, sunflower, maize oil	2, 4, 6, 8, 10 wt.%
Zhang et al. [39]	MoS_2, CNT, ZrO_2	50	Soybean oil	1, 2, 3 vol.%
Zhang et al. [40]	Al_2O_3/SiC	50	Synthetic lipids	6 wt.%
Zhang et al. [41]	MoS_2	50	Palm oil	2 vol.%
Lee et al. [42, 43]	Nanodiamond, Al_2O_3	30, 150	Paraffin oil	2, 4 vol.%
Yang et al. [44]	MoS_2	50	Palm oil	2 vol.%
Jia et al. [6]	MoS_2	50	Soybean oil	6 wt.%

Table 1. Details of investigations on nanofluid parameters for the application of NMQLC in improving lubrication.
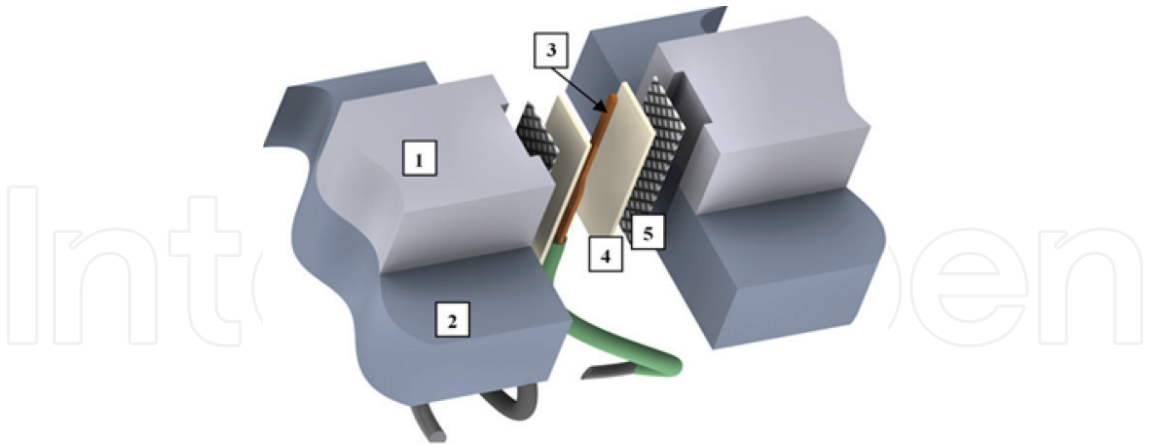

Figure 2. Schematic of single pole configuration thermocouple: where 1-workpiece, 2-workpiece base, 3-thermocouple, 4-mica, 5-varnish layer, 6-grinding wheel [49].

Li et al. [54] analyzed grinding temperature based on the thermal conductivity, viscosity, and contact angle of the nanofluids, and found a lower particle concentration can get a smaller contact angle, thus achieving the optimal heat transfer performance. Lee et al. [55] analyzed

the thermal and flow model for the micro-scale grinding process with experiments. Results showed that the grinding temperatures grinding heat flux into the workpiece and grinding energy partition under NMQLC were much lower than those in the cases of compressed air lubrication and pure MQL. Mao et al. [56] investigated the grinding characteristic under different cooling conditions and the results show that NMQLC grinding can significantly reduce the grinding temperature in comparison to pure water MQL grinding as shown in **Figure 3**.

Table 2 summarizes the details of investigations of nanofluid parameters for the application of NMQLC technique in enhanced heat transfer in grinding zone.
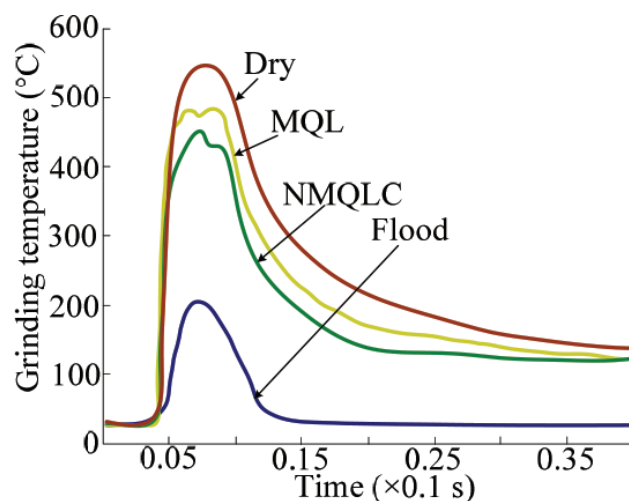

Figure 3. Grinding temperatures under different cooling conditions [56].

Authors	Nanoparticle	Particle size (nm)	Base fluid	Concentration
Mao et al. [50]	Al_2O_3	40, 70, 80	Deionized water, canola oil	1, 3, 5 vol.%,
Yang et al. [51]	Hydroxyapatite, SiO_2, Fe_2O_3, CNTs	Mean particle size is 50 nm, mean length of CNTs is 10–30 μm	Normal saline	2, 4, 6, 8, 10 wt.%,
Yang et al. [52]	Al_2O_3	30, 50, 70, 90	Normal saline	2 vol.%
Li et al. [53]	MoS_2, ZrO_2,CNT, polycrystalline diamond, Al_2O_3, SiO_2	Mean particle size is 50 nm, mean length of CNTs is 10 ~ 30 μm	Palm oil	6 wt.%
Li et al. [54]	CNT	Mean particle size is 50 nm, mean length of CNTs is 10–30 μm	Palm oil	0.5~4 vol.%
Lee et al. [55]	Nanodiamond	30	Paraffin oil	4% vol.%
Mao et al. [56]	Al_2O_3	40	Water	1.2 wt.%

Table 2. Details of investigations for application of NMQLC in enhanced heat transfer in grinding zone.

4. Precise control of temperature field

4.1. Heat source distribution model

In the analysis of temperature fields on workpiece surface, a banding heat source model with continuous equivalent distribution is usually used for heat source in grinding zone to replace the effect of disperse point heat sources to simplify the model [57].

During grinding process, there are three states—scratching, plowing and cutting—between the abrasive grains and workpiece. As shown in **Figure 4** [58], grinding heat sources are under rectangular distribution (heat flux is ξq_w) due to scratching and plowing effects of abrasive grains and triangular distribution (peak heat flux is $u q_w$) due to cutting effect of abrasive grains, where q_w is the average heat flux transferred into workpiece, and ξ and u are, respectively, heat flux coefficients under rectangular heat source distribution and triangular heat source distribution. Abrasive grains exert scratching and plowing effects in OA segment to generate rectangular heat source distribution, and length is a; they exert cutting effect in AL segment to generate triangular heat source distribution [59]; OL is grinding contact length and its value is l. Point B is the position where peak heat flux of triangular heat sources is located, and OB length is b. On this basis, Zhang and Mahdi [59] established a shape functional equation of triangular heat source distribution:

$$
s(x) = \begin{cases}
0 & x \in (-\infty, 0) \\
\xi & x \in (0, a) \\
\dfrac{\xi(b - x) + u(x - a)}{b - a} & x \in (a, b) \\
\dfrac{u(x - 1)}{b - l} & x \in (b, l) \\
0 & x \in (l, +\infty)
\end{cases}
\tag{1}
$$

If abrasive grains are quite pure, there are many abrasive grains exerting scratching and plowing effects under dry grinding state or lubricating performance of grinding fluids is poor, and then comprehensive heat source distribution model is approximate to rectangular heat source
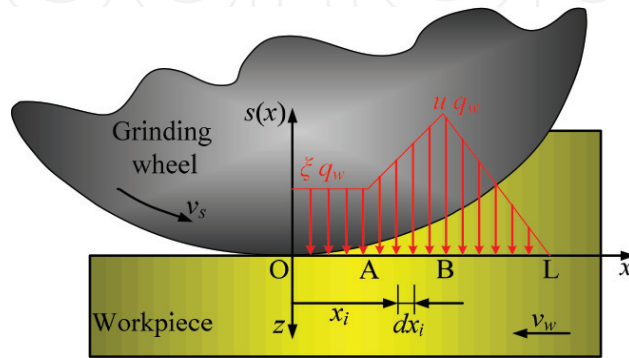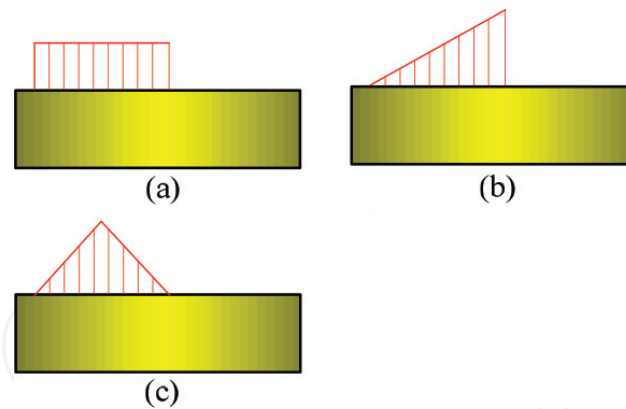

Figure 4. Distribution of heat source [58].

Figure 5. Heat source distribution models in grinding. (a) Rectangular heat source, (b) Right triangular heat source, (c) Isosceles triangular heat source.

distribution model as shown in **Figure 5(a)**. If grinding wheel is dressed very sharp and the lubricating performance of grinding fluids is very good, then abrasive grains mainly exert cutting effect, lengths of scratching and plowing effects are small, and heat source intensity is quite low due to few cutting materials in front end of contact zone. In rear end of contact zone, cutting depth is large, there are many cutting materials and heat source intensity is great, it can be approximate to $a = 0$, $b = l$ and $\xi = 0$, $u = 2$. Comprehensive heat source model can be approximated to right triangular heat source distribution model as shown in **Figure 5(b)**. When $a = 0$, $b = l/2$ and $\xi = 0$, $u = 2$, namely, abrasive grains have strong cutting effect in the middle part of contact zone, generated heat source intensity is great, and comprehensive heat source model can be approximated to isosceles triangular heat source distribution model as shown in **Figure 5(c)**.

4.2. Thermal distribution coefficient

For grinding energies consumed during grinding process, except that a small part of them are consumed on newly generated surface to form needed surface energy, strain energy left on grinding surface layer and kinetic energy for grinding debris to fly out, most part of them are converted into heat energy within contact zone, and these heat energies can be transferred into workpiece, grinding wheel, debris, and grinding fluids in ways of heat conductivity and heat convection. Eqs. (2)–(4) represent the amount of energy transferred into the workpiece (E_w), grinding wheel (E_g), and grinding fluid (E_f), respectively [39]:

$$E_w = \frac{1}{2} \theta_m b' \left[2(k\rho c)_w v_w l_g \right]^{\frac{1}{2}} \tag{2}$$

$$E_g = \frac{1}{2} \theta_m b' \left[2(k\rho c)_g \left(\frac{A_r}{A} \right)_s v_s l_g \right]^{\frac{1}{2}} \tag{3}$$

$$E_f = \frac{1}{2} \theta_m b' \left[2(k\rho c)_f v_s l_g \right]^{\frac{1}{2}} = \frac{1}{2} \theta_m b' \left\{ 2 \left[\varphi(k\rho c)_n + (1-\varphi)(k\rho c)_f \right] v_s l_g \right\}^{\frac{1}{2}} \tag{4}$$

where θ_m is the maximum temperature rise; k, ρ, c stand for thermal conductivity, density, and specific heat, respectively; the subscript g, w, n, f stand for the properties of grain, workpiece,

nanoparticles, and base fluid, respectively; $\frac{A_r}{A}$ is the ratio between the actual and nominal contact areas of grinding wheel and workpiece; v_s is the peripheral speed of grinding wheel; φ is the volume fraction of nanoparticles; b' is the width of grinding wheel; and l_g is the geometric contact arc length.

During grinding, the temperature of the workpiece surface is an important factor to be considered, which is reflected in the thermal distribution coefficient (R) attributed to the workpiece. According to the single abrasive grain model, the amount of heat eliminated by abrasive debris and diffused in convection are too limited to be neglected. During grinding, R can be expressed as follows:

$$R = \frac{E_w}{E_w + E_g + E_f} = \frac{1}{1 + \sqrt{\frac{(k\rho c)_g v_s}{(k\rho c)_w v_w}\left(\frac{A_r}{A}\right)} + \sqrt{\frac{\varphi(k\rho c)_n + (1-\varphi)(k\rho c)_f}{(k\rho c)_w}\frac{v_s}{v_w}}} \tag{5}$$

4.3. Heat transfer coefficient

As NMQLC method can be both heat transfer of normal-temperature gas and boiling heat transfer of nanofluid drop, so this method is the sum of two heat convection methods. According to heat transfer state of single nanofluid drop [60, 61], heat transfer coefficient under NMQLC condition can be solved in three stages: natural convection, nucleate boiling, transition boiling, and film boiling as shown in **Figure 6** [62].

4.3.1. Natural-convection heat transfer stage (I)

When workpiece surface temperature is T_{n1} (lower than boiling point of nanofluid), heat transfer surface will not generate boiling heat transfer and heat transfer enhancement is realized mainly through convective heat transfer of normal-temperature air and convection of nanofluids, mainly being the convective heat transfer of nanofluids [63]. According to Yang's study [28], the nonboiling heat transfer coefficient:

$$h_{n1} = \frac{N_l c_{nf} \rho_{nf} V_l}{\pi r_{surf}^2 \cdot t} + h'_a \tag{6}$$

where N_l is the total number of droplets; c_{nf} is the liquid drop specific heat capacity; ρ_{nf} is the density of nanofluids; V_l is the volume of a single droplet; r_{surf} is the spreading radius of a single liquid drop; t is the total time of grinding process; and h'_a is the convective heat transfer coefficient of air at normal temperature.

4.3.2. Nucleate boiling heat transfer and transition boiling heat transfer stages (II and III)

At the end point of nucleate boiling heat transfer and starting point of transition boiling heat transfer, namely, at critical heat flux point, heat transfer coefficient reaches the maximum value h_{n2}. At the end of transition boiling heat transfer stage and in the initial stage of film boiling heat transfer, heat transfer coefficient reaches the minimum value h_{n3} and computational formula of heat transfer coefficient is as follow:
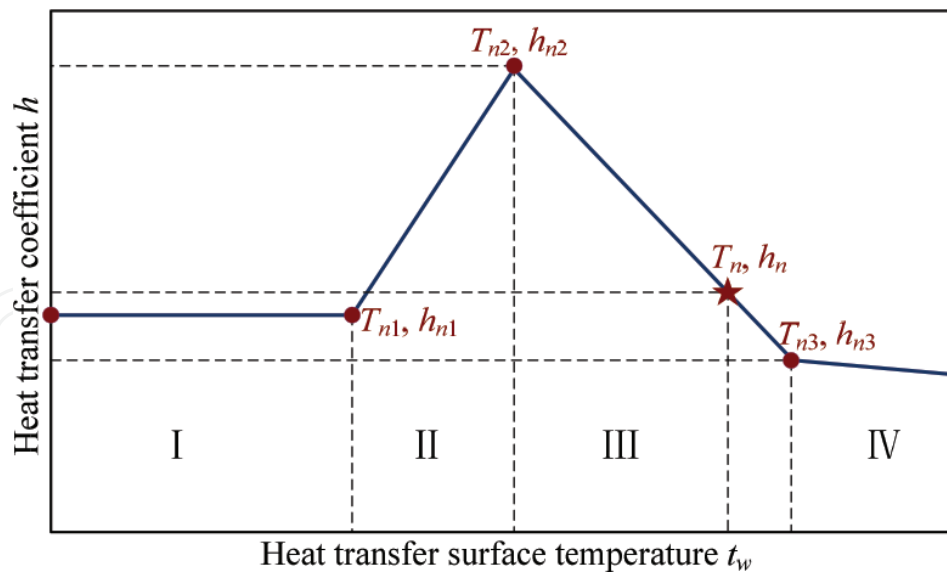
Figure 6. Heat transfer coefficient of grinding surface.

Heat transfer coefficient of critical heat flux density point h_{n2} [64]:

$$h_{n2} = \frac{\left[h_{fa} + c_l\left(T_s - T_{nf}\right)\right]Q'\rho_l}{\pi r_{surf}{}^2\left(T_{n2} - T_{nf}\right)} + h'_a \tag{7}$$

where T_s is the saturation temperature; q'_a is the normal-temperature atmospheric-convection heat transfer quantity; h_{fa} is the latent heat of vaporization; T_{nf} is temperature of nanofluid; c_l is the drop specific heat capacity; and Q' is the nanofluid supply during grinding time.

4.3.3. Transition boiling heat transfer and film boiling heat transfer stages (III and IV)

Computational process of heat transfer coefficient h_{n3} at the end point in transition boiling stage, namely, at starting point in film boiling stage is as follows [65]:

$$h_{n3} = \frac{N_l Q'\rho_l\left[h_{fa} + c_l\left(T_s - T_l\right)\right]\cdot\left[0.027e^{\frac{0.08\sqrt{\ln(We/35+1)}}{B^{1.5}}} + 0.21k_d Be^{\frac{-90}{We+1}}\right]}{b'\cdot l\cdot\left(T_{n3} - T_l\right)} + h'_a \tag{8}$$

Therefore, the heat transfer coefficient h_n can be obtained by the interpolation calculation when the surface temperature of the workpiece is T_n.

4.4. Temperature field control equation and boundary condition

As shown in **Figure 7**, temperature field model in grinding zone is established and the grinding temperature field can be simplified into 2D heat transfer analysis. Field variable T in transient temperature field meets the equilibrium differential equation of heat conduction [66]:
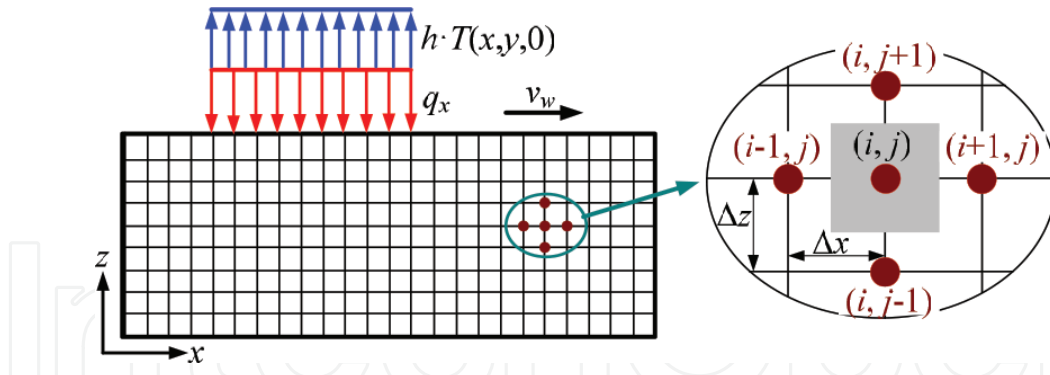
Figure 7. Two-dimensional heat conduction model with nodal network [66].

$$\begin{cases} \dfrac{\partial^2 T}{\partial x^2} + \dfrac{\partial^2 T}{\partial z^2} = \dfrac{1}{\alpha_w}\dfrac{\partial T}{\partial t} \\[2mm] \alpha_w = \dfrac{k_w}{\rho_w c_w} \end{cases} \tag{9}$$

where α_w is the thermal diffusivity.

Difference in the equation of various nodes in internal grids can be obtained based on (9):

$$T_{t+\Delta t}(i,j) = \left[1 - \frac{2\Delta t(k_x + k_z)}{\rho_w c_w \Delta l^2}\right] T_t(i,j) \cdot \frac{\Delta t\{k_x \cdot [T(i,j+1) + T(i,j-1)] + k_z \cdot [T(i+1,j) + T(i-1,j)]\}}{\rho_w c_w \Delta l^2} \tag{10}$$

As for boundary conditions analysis in grinding zone, coordinate node (i, j) on the workpiece surface is taken as an example. According to energy conservation law [67, 68], the temperature at the node (i, j) after Δt:

$$T_{t+\Delta t}(i,j) = \frac{\Delta t}{\rho_w C_w \Delta l^2}\{k \cdot [T(i-1,j) + T(i+1,j) + T(i+1,j)\text{-}3T(i,j)] + [q - h(T_t - T_a)] \cdot \Delta l\} + T(i,j) \tag{11}$$

4.5. Precise control of temperature field

The temperature field at different times during the steady process can be obtained by solving the difference Eq. (11). **Figure 8** shows the temperature isoline under NMQLC at different times and the corresponding time-space distribution of surface temperature. It can be seen that the grinding process can be divided into three stages, namely, cut-in, steady state, and cut-out [66]:

Cut-in: when abrasive grains start to contact and cut the workpiece, the undeformed chip thickness increases gradually and the heat generated on the grinding interface begins to be transmitted into the workpiece surface.

Steady state: the undeformed chip thickness kept at the mean value and workpiece surface temperature stops increasing. The temperature field reaches the steady state.

Cut-out: the undeformed chip thickness decreases gradually in the cut-out region. According to the theory of heat transfer, the heat conduction in the cut-out region is reduced considering the
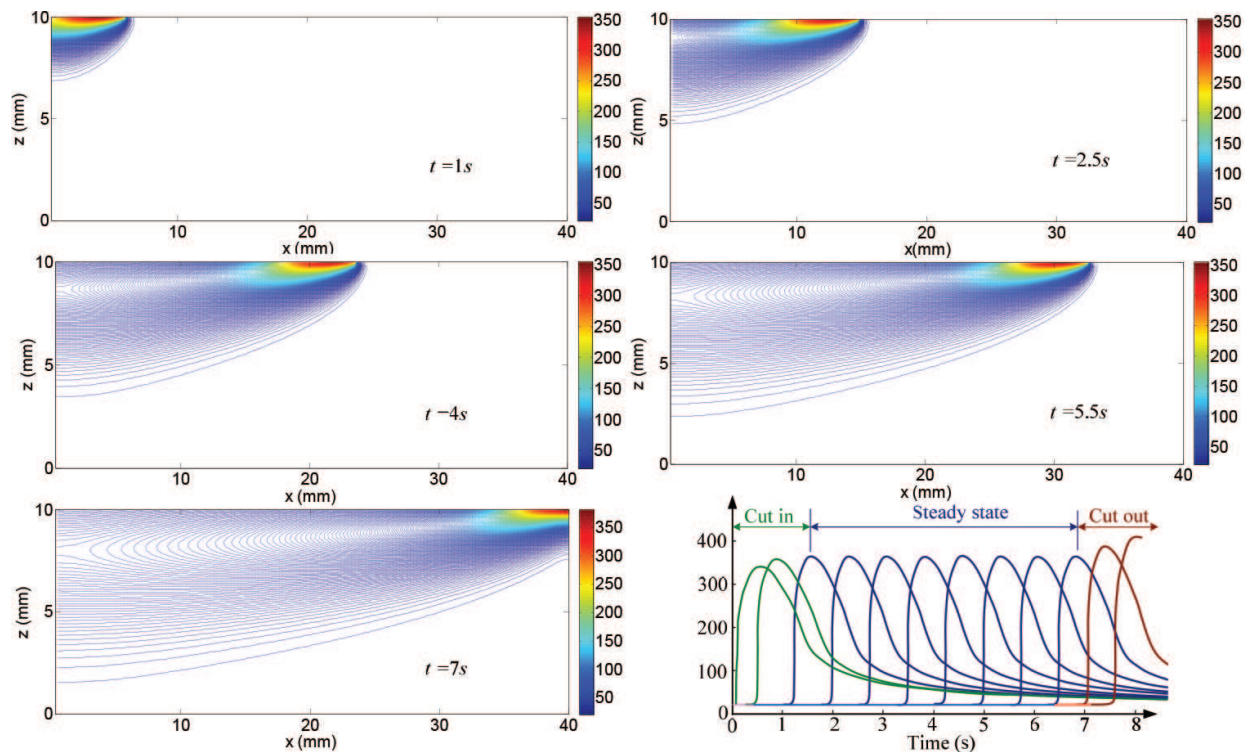
Figure 8. Distributions of the grinding temperature and temperature curves in different states [68].

fixed heat generated on the grinding surface [66]. As the thermal conductivity of the air is very low, more heat is concentrated in the grinding zone, thus increasing the grinding temperature.

5. Conclusions

This chapter has presented a review of published researches in the application of NMQLC during grinding. The following conclusions may be drawn from the present literature review:

1. The amount of nanofluids using NMQLC is very small (7.5–350 mL/h based on published literatures) compared with flood lubrication (usually 60 L/h), so this technique is an environmentally friendly lubrication-cooling method.

2. NMQLC can improve the lubrication condition in grinding area and reduce the friction coefficient effectively, thus reducing the grinding force and specific grinding energy, reducing workpiece surface roughness, and improving the life of grinding wheel.

3. NMQLC can strengthen the heat transfer in the grinding zone that NMQLC could realize a lubrication-cooling effect close to that of flood lubrication.

4. Based on published literatures, nanoparticles that have effective lubrication properties are TiO_2, SiO_2, Al_2O_3, MoS_2, ZnO, and nanodiamond; nanoparticles that have effective cooling properties are CuO, NiO, CNTs, and SiC. A mixed use of nanoparticles with good lubricated properties and nanoparticles with good cooling properties can obtain lower grinding force, grinding temperature, and better surface quality.

5. The lubricating performance of oil-based nanofluid is better than that of water-based nanofluid and the cooling effect is just reverse.

6. Recommendations for future research

The NMQLC technique has been applied by a large number of researchers and can obtain good lubrication and cooling effect. However, there are three points of misgivings based on the summary of available literatures. In order to achieve precision control of the grinding temperature field, more attention is needed to study these misgivings:

1. Most researchers prepare nanofluid using oil or water as base fluid and all can obtain good lubrication or cooling effect close to that of flood lubrication; however, for the addition of nanoparticles into ester, Sridharan and Malkin [69] did not get the ideal result. It is found that when using plain ester oil as base medium, workpiece thermal distortion for NMQLC grinding was reduced by about the same relative amount as the specific energy compared with pure ester oil, which suggests that the addition of nanoparicles to ester oil maybe had no significant effect on workpiece cooling.

2. Li et al. [68] investigated NMQLC grinding temperature using different workpiece materials: 45 steel, Ni based alloy, and cast iron. Experimental results on specific grinding force and grinding temperature revealed that the grinding condition is inapplicable to grinding 45 steel, indicating that the NMQLC method is not applicable to all workpiece materials.

3. Only a few researchers have studied the effect of nanofluid parameters, including the nanoparticle concentration and size, on grinding performance. Some researchers have proved that a higher nanoparticle concentration is more effective for reducing grinding forces [43, 70]. But for the effect of particle size, there is no unified conclusion. The conclusion of Lee [43] and Yang [52] is that the smaller size of nanoparticles is more effective for reducing grinding forces and temperature; Mao [50] found that, when the diameter of nanoparticle increases, tangential grinding force and temperature decreases slightly while the surface finish is deteriorated.

Acknowledgements

Nomenclature

CNT   carbon nanotubes

EHD   electro-hydro-dynamic

hBN   hexagonal boron nitride

MWCNTs   multi-walled carbon nanotubes

MQL   minimum quantity lubrication

NMQLC   nanofluid minimum quantity lubrication cooling

UAG   ultrasonic-assisted grinding

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