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Specific grinding energy and surface roughness of nanoparticle jet minimum quantity lubrication in grinding

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Abstract Nanoparticles with the anti-wear and friction reducing features were applied as cooling lubricant in the grinding fluid. Dry grinding, flood grinding, minimal quantity of lubrication (MQL), and nanoparticle jet MQL were used in the grinding experiments. The specific grinding energy of dry grinding, flood grinding and MQL were 84, 29.8, 45.5 J/mm^3, respectively. The specific grinding energy significantly decreased to 32.7 J/mm^3 in nanoparticle MQL. Compared with dry grinding, the surface roughness values of flood grinding, MQL, and nanoparticle jet MQL were significantly reduced with the surface topography profile values reduced by 11%, 2.5%, and 10%, respectively, and the ten point height of microcosmic unflatness values reduced by 1.5%, 0.5%, and 1.3%, respectively. These results verified the satisfactory lubrication effects of nanoparticle MQL. MoS_2, carbon nanotube (CNT), and ZrO_2 nanoparticles were also added in the grinding fluid of nanoparticle jet MQL to analyze their grinding surface lubrication effects. The specific grinding energy of MoS_2 nanoparticle was only 32.7 J/mm^3, which was 8.22% and 10.39% lower than those of the other two nanoparticles. Moreover, the surface roughness of workpiece was also smaller with MoS_2 nanoparticle, which indicated its remarkable lubrication effects. Furthermore, the role of MoS_2 particles in the grinding surface lubrication at different nanoparticle volume concentrations was analyzed. MoS_2 volume concentrations of 1%, 2%, and 3% were used. Experimental results revealed that the specific grinding energy and the workpiece surface roughness initially increased and then decreased as MoS_2 nanoparticle volume concentration increased. Satisfactory grinding surface lubrication effects were obtained with 2% MoS_2 nanoparticle volume concentration.

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1. Introduction

Grinding, which is part of processing finishing approaches, is used to remove materials with abrasives. Therefore, workpiece surface quality should be precise. Grinding depth is smaller,

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resulting in larger specific grinding energy, compared with that of cutting and milling.[1,2] Thus, the lubrication of the grinding surface should be considered. The lubrication of the grinding surface is influenced by various factors, such as grinding parameters, abrasive particle size, workpiece material properties, and cooling lubrication approach. Cooling lubrication approaches have also evolved, improved, and are optimized toward aspects, such as energy conservation, emission reduction, ecological friendly, and high efficiency with the development of grinding technology.[3]

The earliest cooling lubrication approach in grinding is flood grinding, in which large amount of grinding fluid is poured as a continuous feed flow into the grinding wheel and workpiece interface. The excellent characteristic lubrication of grinding fluid enables it to form an oil film on the workpiece surface and reduce frictional coefficient and grinding force between the grinding wheel and the workpiece.[4] Grinding fluid also aids in lubricating, washing, removing debris, and rust protection.[5] However, the increasing extensive application of grinding fluid results in considerable application costs.[6] Moreover, leakage and volatilization of grinding fluid cause pollution and inflict hazards to the environment and the human body.[7] Therefore, a cooling lubrication approach is necessary for ecological and clean production grinding process.

Dry grinding is the earliest environmentally friendly grinding processing technique. Given that grinding fluid is not used, the technique is evidently more environment-friendly; however, the massive heat from grinding cannot be dispersed from the grinding surface instantly. Thus, the heat delivered to the grinding wheel and workpiece base through the grinding surface results in a locally high temperature on the workpiece surface and even burns.[8] This phenomenon, which is mainly due to insufficient cooling and lubrication on the grinding surface, eventually causes poor workpiece surface quality and short grinding wheel service life.[9]

Minimum quantity lubrication (MQL) is a technique between dry grinding and flood grinding to ensure cooling lubrication effects. MQL uses minimal quantity of grinding fluid, which is jet with high-pressure gas to the grinding zone. This technique integrates the advantages of flood grinding and dry grinding.[10] In MQL, the grinding wheel unit width for grinding fluid usage is 30–100 mL/h and 60 L/h for flood grinding fluid. The cooling lubrication effect of MQL greatly improved compared with that of dry grinding.[11,12] Dhar et al.[13] demonstrated that MQL cutting force is reduced by 5%–15% and the grinding tool service life in MQL is prolonged compared with dry grinding. Gaitondea et al.[14] indicated that MQL improves workpiece surface quality compared with dry grinding. Barczak et al.[15] applied the precision surface grinding machine in the experimental research of the grinding power, the grinding force, the grinding temperature, and the surface roughness under three cooling lubrication conditions, namely, MQL, flood grinding, and dry grinding. They found that MQL grinding power and grinding force under specific conditions are smaller than those of dry grinding and flood grinding. Moreover, MQL grinding temperature and workpiece surface quality are better than that of dry grinding and less desirable than that of flood grinding. Silva et al.[16] studied the surface completeness, specific grinding energy, and grinding wheel wear under dry grinding, flood grinding, and MQL conditions. They found that MQL provides effective lubrication but insufficient cooling effects, thus deteriorating the workpiece surface completeness compared with flood grinding. They also studied the workpiece surface completeness in MQL grinding. Sadeghi et al.[17] conducted experiments to identify the effects of changing grinding parameters in titanium alloy MQL grinding on a workpiece surface quality and the grinding force. Wang et al.[18] conducted experiments on a precision numerical control grinding machine to compare the minimum cutting depth (5 μm) of grinding using MQL oil film with a drop of working fluid, emulsion, a soluble liquid, a small amount of water mist, and an MQL oil mist working fluid.

A comprehensive consideration of MQL cooling lubrication performance showed that workpiece surface quality is worse after MQL grinding than after flood grinding, this finding is mainly attributed to the need of further improving cooling and lubrication performance.

Solid heat-transfer enhancement theory is considered to compensate for the insufficient cooling effects of MQL. Solid particles have advantageous heat-transfer capabilities than liquid and gas; moreover, the surface areas and heat capacities of nanoparticles are greater than those of particles of millimeter or micrometer scale with similar particle volume fractions.[19,20] Hence, the capacity of heat transmission of nanofluids would increase dramatically. Therefore, according to solid heat-transfer enhancement theory, nanoparticle can be added in the grinding fluid using MQL. The mixed solid nanoparticles, lubricant (oil or oil water mixture), and compressed air are jet to the grinding zone after pulverization. MQL lubricant mainly works on lubrication. Nanoparticles can enhance the heat exchange capability of grinding fluids to cool and to lubricate the grinding zone.[21] Krajnik et al.[22] evaluated the properties of nanofluids and analyzed its industrial application by focusing on the heat exchanges in cooling and friction lubrication. The development of nanofluids as new coolants and lubricants is expected with great prospects. Hisakado et al.[23] added 10–50 nm copper and nickel nanoparticles to the paraffin base oil to produce nanoparticle lubricants and investigated its frictional properties. The results indicated that under similar conditions, the coefficient of friction is reduced by at least 18% after adding copper and nickel nanoparticles in the paraffin wax. This finding shows that nanoparticles can significantly improve the anti-wear and friction-reducing performance of lubricating oils. Lee et al.[24] probed the application of nanoparticle jet MQL into grinding. They selected polycrystal diamond and Al_2O_3 nanoparticles to generate grinding fluids with paraffin. The results demonstrated that grinding force significantly decreases and workpiece surface quality is improved. They also verified that nanoparticle size and concentration are two important parameters that affect grinding performance. Prabhu and Vinayagam[25] added carbon nanotubes in MQL grinding and studied its effect on workpiece surface smoothness. They found that adding multi-walled nanotubes in grinding can improve surface smoothness. Sayuti et al.[26] applied carbon nanotubes as nanoparticle additives in lubricants for aviation duralumin A grinding. They compared the cutting forces and surface qualities of different concentrations of the mixed mineral oils. The cutting force and the surface roughness of the mixture are reduced by 46.32% and 21.99%, respectively, compared with those of pure oil. Alberts et al.[27] studied cooling lubrication performance by adding graphite nanoparticle in the grinding fluid during a steel chisel tool

grinding. The grinding force and the specific grinding energy of graphite nanoparticle MQL are reduced, and the workpiece surface quality is significantly improved compared with those of pure oil MQL. Prabhu and Vinayagam[28] used carbon nanotubes as additives to study the workpiece surface morphology of a steel chisel tool steel grinding. They examined the fractal dimensions of different processing surfaces and measured the surface roughness. Liao et al.[29] selected MQL and nanoparticle jet MQL to conduct grinding experiments. Experimental results showed that the grinding force and the frictional coefficient in nanoparticle jet MQL are smaller than those in MQL, and the workpiece quality in nanoparticle jet MQL is better. Vasu and Reddy[30] added Al_2O_3 nanoparticle with different volume fractions in vegetable oil as the grinding fluid and used nanoparticle jet MQL in a ferrous-nickel grinding experiment. They also compared dry grinding with MQL grinding. According to their experimental results, workpiece surface smoothness and cooling effects are improved by nanoparticle, and the cutting force and tool abrasion are greatly reduced. Mao et al.[31] also added Al_2O_3 nanoparticle in a nanoparticle jet MQL grinding experiment. They compared the grinding parameters (i.e., grinding temperature, grinding force ratio, and workpiece surface texture and roughness) with dry grinding, flood grinding, and MQL. Their results showed that the grinding parameters, such as grinding temperature, under nanoparticle jet MQL are only second to those in flood grinding. Shen et al.[32] added Al_2O_3, polycrystal diamond, and CNT nanoparticles in the grinding fluid for nanoparticle jet MQL grinding experiments. They identified the surface temperature, grinding force, G ratio, and surface roughness during the grinding. Results demonstrate that the lubricating features and high thermal conductivity of the nanoparticles greatly improved the workpiece surface quality and prolonged the grinding wheel service life. Moreover, the energy ratio is considerably smaller than that of MQL. Nguyen et al.[33] added nanoparticle in vegetable oils in the grinding to analyze the enhancement of lubrication performance on the grinding surface. Tsai and Jian[34] used 0.1%, 0.5%, 1%, 3%, and 5% graphite nanoparticle weight fractions in nanoparticle jet MQL grinding. They studied the surface roughness, grinding wheel wear, grinding temperature, and grinding force and found that these parameters are lower than those of traditional grinding. To ensure cooling and lubrication performance, they recommended a less than 5% graphite nanoparticle weight fraction in nanoparticle jet MQL grinding. Kalita et al.[35] added MoS_2 nanoparticle in the grinding fluid to discuss its effect on the specific grinding energy and frictional coefficient of cast iron grinding. They used paraffin oil and vegetable oil as grinding fluid base oils. They compared their results with those of flood grinding and MQL and found that adding nanoparticle reduces power consumption and improves grinding wheel wear and surface quality. Most studies focused on the effects of different cooling lubrication approaches, changes in grinding parameters, different grinding fluid base oils, different nanoparticle types, or different nanoparticle concentrations on cooling and lubrication performance during grinding. However, these studies are not comprehensively integrated. The present study integrated various cooling lubrication approaches and selected the cooling lubrication approach with the optimal lubrication performance through comparisons. Results were also compared, optimized, and refined to select the nanoparticle category and volume concentration with better lubrication performance. Thus, this study aimed to provide a remarkably significant and effective experimental approach for grinding research.

2. Nanoparticle jet MQL grinding

Nanoparticle jet MQL grinding is an approach that adds solid nanoparticle in the grinding fluid for MQL grinding and jets the pulverized nanoparticle lubricant (oil or oil–water mixture) with high-pressure gases (0.4–0.65 MPa) into the grinding zone. This approach only consumes 30–100 mL/h of grinding fluid per unit width of the grinding wheel.[36] Nanoparticle droplets are dropped on the workpiece and the grinding wheel to cool and lubricate. The diagram of nanoparticle jet MQL grinding is shown in Fig. 1. In Fig. 1, v_s is the peripheral speed of the grinding wheel (m/s), v_w is the feed velocity (m/s), a_p is the grinding depth (mm), b is the grinding width (mm).

Nanoparticles as additives in grinding fluid base oil can increase the thermal conductivity of the grinding fluid and the convective heat-transfer capacity of nanoparticle jet flow according to theory of heat-transfer enhancement by solids. Nanoparticle addition also effectively improves the cooling performance of grinding surfaces.[37] Nanoparticles have efficient lubrication features in addition to their satisfactory cooling performance.

In terms of friction and lubrication, nanoparticles have tribological properties, such as anti-wear, friction reducing performance, and high load-carrying capacity.[38,39] Nanomaterials behave similar to fluid molecules because of their small sizes. The strong Brownian motion of nanoparticles is conducive to stable suspension rather than precipitation and shows excellent fluid performance, stable performance, and uniform components. Grinding fluid base oils can be applied to workpiece surface to form a liquid film, which serves as lubricant.[40] Meanwhile, the nanoparticles that jetted with the grinding fluid base oil to the grinding surface exhibit remarkable lubricating characteristics between the abrasives and the workpiece. The lubricating functions can be summarized similar to ball bearing, protective film, and wear restoration. The lubricating effects of nanoparticles in the abrasive–workpiece interface are shown in Fig. 2.

Similar to ball bearing, most nanoparticles are spherical or spheroidal with remarkable diffusivity and self-diffusivity. When an abrasive moves on the workpiece surface with the rotation of the grinding wheel, the nanoparticles fill the abrasive–workpiece interface, turning the contact between the abrasive and workpiece from sliding friction to rolling friction. Given that rolling friction generates smaller frictional

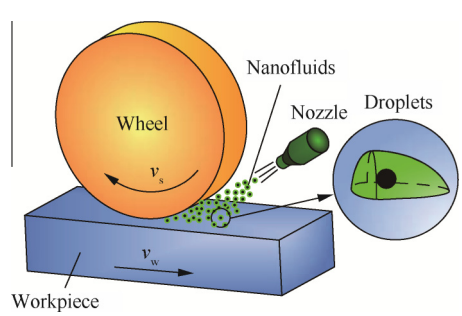


Fig. 1 Schematic of nanoparticle jet MQL grinding.

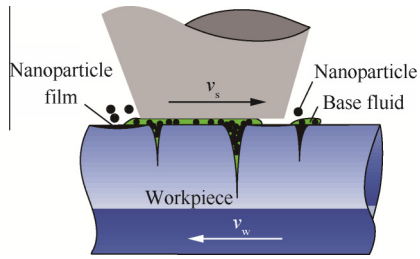


Fig. 2 Schematic of nanoparticles in grinding interface.

resistance than sliding friction, nanoparticles serve similar to ball bearing and undertake most of the frictions and loads on the grinding surface, thereby reducing grinding force and frictional coefficient and improving lubrication performance.[41] In addition, nanoparticles possess excellent extreme pressure characteristic that can protect the oil film, which is formed by the base oil, from damages and prevent the abrasive from bonding with the workpiece.

Nanoparticles precipitate or function as protective film on workpiece surfaces under the influence of magnetic field force. Nanoparticles on the grinding surface can possibly melt or half melt under heavy loads because of temperature influence in the workpiece grinding area.[42,43] They form a layer of nanoscale or microscale nanofilms on the workpiece surface, as shown in Fig. 2. The thin film appears flocculent because grinding is a technique for removing materials.[44,45] Nanoparticles of special materials can be diffused, penetrated on the grinding surface, or can form new materials with elements of workpiece materials. Surface modification of workpiece material can be conducted through in-situ tribochemical treatment, thus enhancing workpiece surface and improving surface abrasion resistance and workpiece surface quality.

Microscratches, grooves, or cracks on the workpiece surface can be formed under the influence of applied force or uneven distribution of thermal stress distribution during grinding. Under the grinding fluid and the sliding friction of the abrasives along the workpiece surface, nanoparticles fill the microscratches, grooves, or cracks on the workpiece surface. Under factors, such as pressure, friction, and locally high temperature, nanoparticles exhibit eutectic reaction with the workpiece contact material.[46] Nanoparticles are fused with the workpiece material, thus repairing surface defects and damages on the workpiece. The workpiece grinding surface is fixed and repaired to a certain degree through physical and chemical reactions.[47,48]

3. Evaluation of workpiece surface quality

3.1. Specific grinding energy

Specific grinding energy is the energy consumed in removing unit volume of metal materials, which can be expressed as follows:

$$E_e = \frac{P}{V} = \frac{F_t(v_s \pm v_w)}{v_w a_p b} \tag{1}$$

where P is the grinding power (W), V is the workpiece volume (mm^3/s), F_t is the tangential grinding force (N), "+" indicates upgrinding, and "−" indicates downgrinding.

The specific grinding energy is significant because it reflects the mechanism and degree of abrasive and workpiece interference.[49] The specific grinding energy is also an evaluation indicator of grinding fluid lubricating capability. Sufficient lubrication of the grinding zone by grinding fluid can reduce the friction between the abrasive and workpiece, decrease grinding force, and generate low and stable specific grinding energy. Different lubrication conditions can generate different tangential grinding force (F_t) under similar grinding parameters. In the experiment, the tangential grinding force (F_t) can be obtained with a grinding dynamometer, which can be substituted into Eq. (1) to calculate the specific grinding energy.

Given that the specific grinding energy can reflect the lubricating condition of the grinding surface, the grinding force and power consumption during grinding can be estimated. The tangential grinding force and the power to remove unit volume of materials also increase when the grinding surface has poor lubrication conditions, and eventually, the workpiece surface quality becomes deteriorated. By contrast, the workpiece material can be easily cut with small tangential grinding force and small and stable specific grinding energy when the grinding surface is sufficiently lubricated, resulting in a satisfactory workpiece surface quality.

3.2. Surface roughness

Grinding is a finishing technique; however, tiny peak valleys and roughness on the workpiece surface remain after the process. The surface roughness can reflect the error size with microcosmic geometrical shape on the workpiece surface.

Workpiece surface roughness and surface topography precisely reflect workpiece surface quality after grinding. Workpiece surface quality can be calculated based on surface topography profile (R_a) and ten point height of microcosmic unflatness (R_z). The surface roughness, and R_a and R_z values along the workpiece vertical grinding direction can be measured with a contour measurement analyzer under different conditions[50] to further calculate the standard deviations (S) of R_a and R_z. Workpiece surface quality under different lubricating conditions can be clearly compared based on R_a, R_z, and S values.

4. Experimental design

An experimental approach to conduct the experimental research was devised to further analyze the effects of lubrication conditions under different cooling lubrication conditions on workpiece surface roughness. A K-P36 CNC surface grinder was used in the experiment. The grinding wheel was made of vitrified bond alumina WA80MV12P. The abrasive had a 508 μm particle size. A Hardened Steel 45 with dimensions of 40 mm × 30 mm × 60 mm was used as workpiece. The control of a single variable with an experimental philosophy of gradual advancement and optimization through comparisons was adopted in this experiment. The experiment was designed as follows.

4.1. Experiment 1

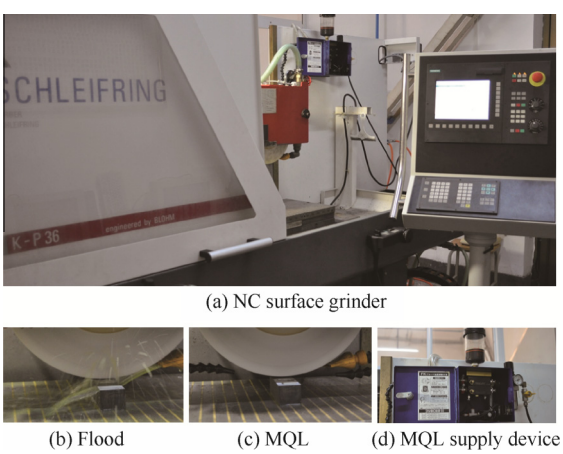
Four cooling lubrication approaches, namely, dry grinding, flood grinding, MQL, and nanoparticle jet MQL, were set in

the experiment for grinding treatment. The grinding forces under the four cooling lubrication conditions and their effects on workpiece surface quality were analyzed under similar grinding parameters. The grinding force was described as the average value of 100 randomly selected data points in four grinding steps. Based on the measured results, the specific grinding energy and the workpiece surface roughness were obtained, thus enabling the comparison of the lubrication performance of the four cooling lubrication conditions. Fig. 3 and Table 1 present the equipment and grinding parameters used in the experiment.

Among the four cooling lubrication approaches in this experiment, the dry grinding did not require any cooling measures, and the flood grinding adopted Syntilo9930-water base grinding fluid with 5% volume fraction, as shown in Fig. 3(b). Vegetable oil as base oil (colza oil), which was jet into the workpiece surface using high-pressure gas, was used in both MQL and nanoparticle jet MQL. The fluid supply approach is shown in Fig. 3(c), with similar liquid supply amounts and air pressure values set in all approaches. MQL equipments are shown in Fig. 3(d). The only difference was that 1% nanoparticle volume fraction was added in nanoparticle jet MQL grinding fluid. The parameters of the grinding fluid on the four cooling lubrication approaches are shown in Table 2.

4.2. Experiment 2

According to the results of Experiment 1, the lubricating conditions on the grinding surface under four cooling lubrication approaches were identified. Nanoparticle jet MQL demonstrated remarkable lubrication performance compared with those of three cooling lubrication approaches. Thus, we further studied the lubrication performance of nanoparticle. Different types of nanoparticles in similar grinding fluid base oil were added to identify the lubrication performance, including MoS_2, CNT, and ZrO_2. Grinding fluids with 1% volume concentration were prepared for the experiment, and the nanoparticle type with the optimal lubrication performance was selected.



(a) NC surface grinder

(b) Flood (c) MQL (d) MQL supply device

Fig. 3 Experimental equipment in surface grinding process.

Table 1 Grinding experiment conditions.

Grinding condition	Parameter setting
Grinding way	Plane grinding, upgrinding
Grinding equipment	K-P36 NC grinding machine
v_s	35 m/s
v_w	0.05 m/s
a_p	20 μm

4.3. Experiment 3

According to the results of Experiment 2, the nanoparticle type with the optimal lubrication performance was selected. Grinding fluids with 1%, 2%, and 3% volume concentrations were prepared, and the nanoparticle volume concentration with the optimal lubrication performance was selected.

The different grinding fluids, nanoparticle categories, grinding fluid base oils, and grinding fluid nanoparticle volume concentrations used in Experiments 2 and 3 are shown in Table 3.

5. Experimental results and analysis

In this study, the specific grinding energy and effects of different cooling lubrication conditions on the surface roughness of workpiece were investigated to determine the lubrication conditions on the workpiece surface during grinding. The tangential grinding force and the grinding surface roughness R_a and R_z values were also measured in the experiment.

5.1. Analysis of results from Experiment 1

Different cooling lubrication approaches can generate different lubrication performance on the grinding surface. Under the four cooling lubrication conditions, the grinding force on the grinding surface also changed. The YDM-III 99 three-dimensional dynamometer was used in this study to measure the grinding force; the grinding experiment diagram is shown in Fig. 4. The average tangential grinding forces (F_t) at grinding above a stable status under different cooling conditions are shown in Table 4.

Remarkable differences in the tangential grinding forces obtained under four cooling lubrication approaches were observed, as shown in Table 4. This finding can be mainly attributed to the different lubrication conditions on the grinding surface. The frictional coefficient of the grinding surface was calculated as the ratio of the tangential and the normal grinding forces. A comparison of the frictional coefficients under the four cooling lubrication approaches is shown in Fig. 5(a).

Dry grinding produced the maximum tangential grinding force, which was mainly attributed to the absence of grinding fluid lubrication. Thus, the frictional coefficient on the grinding surface was as high as 0.45. In flood grinding, considerable amount of grinding fluid was used in cooling and lubrication. Thus, a frictional coefficient of as low as approximately 0.21 was obtained under the lubricating effects of liquid film on the grinding surface. MQL significantly produced lower tangential grinding force and frictional coefficient compared with dry grinding. However, these parameters were still less excellent than those in flood grinding. Nanoparticle jet MQL offset the lubrication performance of MQL, which was mainly due to the nanoparticle anti-wear and friction reducing performance on the grinding surface. The tangential grinding force and

Table 2 Parameters on the four cooling lubrication approaches.

Cooling approach	Parameter setting
Flood	Water-based grinding fluid Syntilo9930, Flow rate = 100 L/min
MQL	Pure oil-based (colza oil), Flow rate = 30 mL/h, air pressure = 0.5 MPa
Nanoparticle jet MQL	Pure oil-based (colza oil), MoS_2 nanoparticle, Diameter = 50 nm, Volume concentration = 1%, Flow rate = 30 mL/h, Air pressure = 0.5 MPa
Dry	No

Table 3 Grinding fluid compositions.

Nanoparticle	Diameter	Base fluid	Volume concentration
MoS_2	50 nm	Colza oil	1%, 2%, 3%
CNT	50 nm	Colza oil	1%, 2%, 3%
ZrO_2	50 nm	Colza oil	1%, 2%, 3%

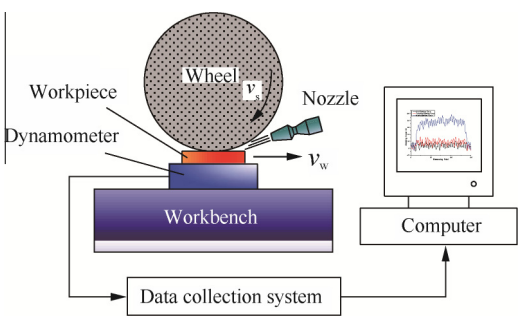


Fig. 4 Grinding experiment diagram.

Table 4 Tangential grinding force.

Cooling approach	Dry	Flood	MQL	Nanoparticle jet MQL
F_t (N)	48	17	26	19

frictional coefficient on the grinding surface were significantly reduced. The calculation of the specific grinding energy could reflect the power consumption on the grinding surface, thereby reflecting the lubrication condition. The tangential grinding force and grinding parameters were substituted into Eq. (1) to generate the specific grinding energy under the four cooling lubrication approaches, as shown in Fig. 5(b).

According to Fig. 5(b), dry grinding produced the maximum specific grinding energy (84 J/mm^3), which indicated that the energy consumed in removing unit volumes of the workpiece material was high. This finding also demonstrated a less satisfactory lubrication condition on the grinding surface. Flood grinding produced the lowest specific grinding energy (29.8 J/mm^3), which indicated that it demonstrated the best lubrication condition on the grinding surface.

The specific grinding energy of MQL was significantly reduced compared with dry grinding but was still higher than that of flood grinding (45.5 J/mm^3). The added nanoparticles in nanoparticle jet MQL grinding fluid greatly decreased the specific grinding energy to 32.7 J/mm^3 compared with that of MQL. The grinding force and power consumption from grinding were reduced, which indicated that the lubrication condition on the nanoparticle jet MQL grinding interface was satisfactory and even close to that that of flood grinding. Therefore, nanoparticle jet MQL produces a satisfactory workpiece surface quality.[51]

The workpiece surface quality could directly reflect the effect of lubrication performance on workpiece surface. A S-3500N scanning electron microscope was used to scan the workpiece surface under the four cooling lubrication approaches. The surface morphologies of workpieces are shown in Fig. 6.

Fig. 6(a)-(d) shows the workpiece surface morphologies under dry grinding, flood grinding, MQL, and nanoparticle jet MQL, respectively. An uneven workpiece surface texture with serious material stacking and adhesion was observed from dry grinding (Fig. 6(a)). The workpiece surface quality was seriously damaged. Fig. 6(b) shows the remarkable workpiece surface quality in flood grinding, with even and clear surface texture. Meanwhile, the workpiece surface topography in

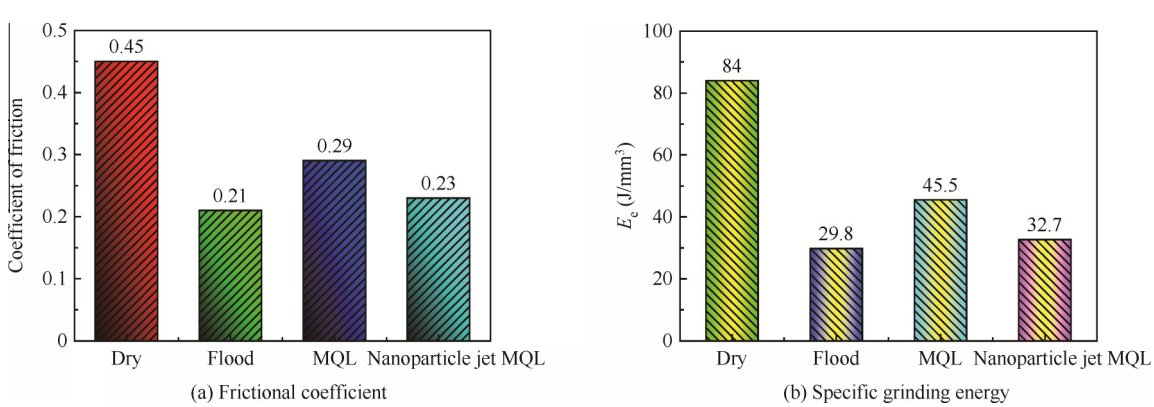
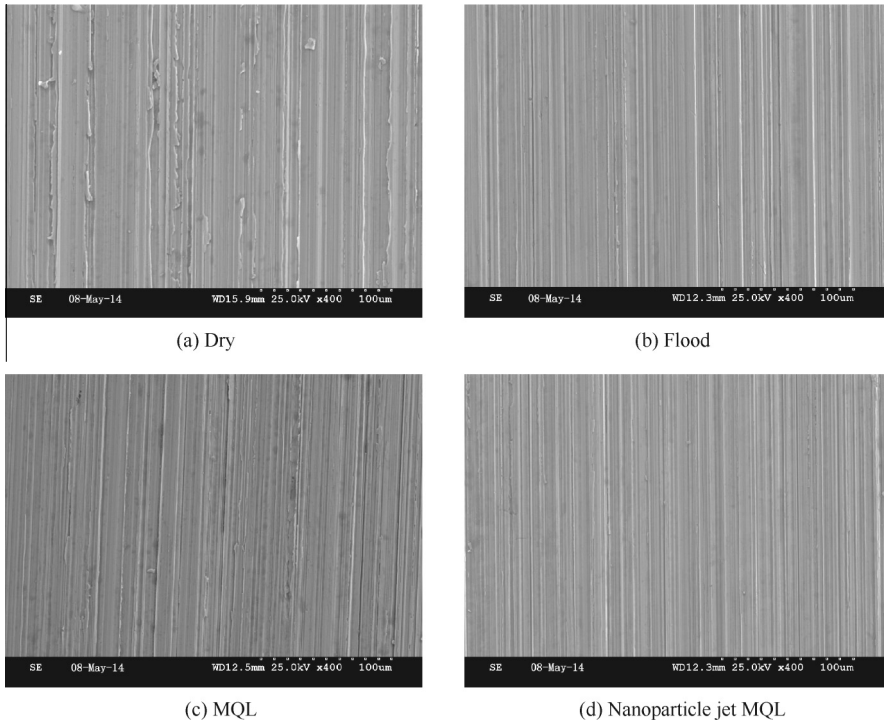


Fig. 5 Frictional coefficient and specific grinding energy under the four cooling lubrication approaches.



(a) Dry (b) Flood (c) MQL (d) Nanoparticle jet MQL

Fig. 6 Surface topography of the workpieces under the four cooling lubrication approaches.

MQL was better compared with that of dry grinding. Moreover, surface material accumulation and adhesion were relieved. However, these results are not as good as those in flood grinding as shown in Fig. 6(c). The problems in MQL were resolved by nanoparticle jet MQL, which also improved material accumulation and adhesion. The workpiece surface quality achieved a level close to that of flood, as shown in Fig. 6(d). Workpiece surface quality can be compared with surface roughness. The measured profiles were analyzed to identify the workpiece surface roughness R_a and R_z values along the vertical grinding direction under the four cooling lubrication conditions. The R_a and R_z values were average values of 16 measurements on a similar surface to further calculate the standard deviation S of R_a and R_z values, as shown in Fig. 7.

According to Fig. 7, the highest R_a and R_z values along the direction vertical to the workpiece texture were obtained in dry grinding. Surface roughness was significantly reduced in the other three cooling approaches compared with that in dry grinding. R_a value was reduced by 11%, 2.5%, and 10% in flood grinding, MQL, and nanoparticle jet MQL, respectively. R_z value was reduced by 1.5%, 0.5%, and 1.3% in flood grinding, MQL, and nanoparticle jet MQL, respectively. The standard deviation S of R_a under dry grinding, flood grinding, MQL, and nanoparticle jet MQL were 0.077, 0.023, 0.054, and 0.031, respectively. The standard deviation S of R_z under dry grinding, flood grinding, MQL, and nanoparticle jet MQL were 0.376, 0.089, 0.247, and 0.115, respectively. By comprehensive examination revealed that flood grinding demonstrated the smallest surface roughness and the best surface quality. Surface roughness reduction was also observed in MQL, but with limited efficiency. Nanoparticle jet MQL effectively reduced workpiece surface roughness, which is close to that of flood grinding, compared with that of MQL. A comprehensive consideration of energy conservation, cooling lubrication performance, and other factors revealed that nanoparticle jet MQL could be used to replace flood grinding as a cooling lubrication approach.

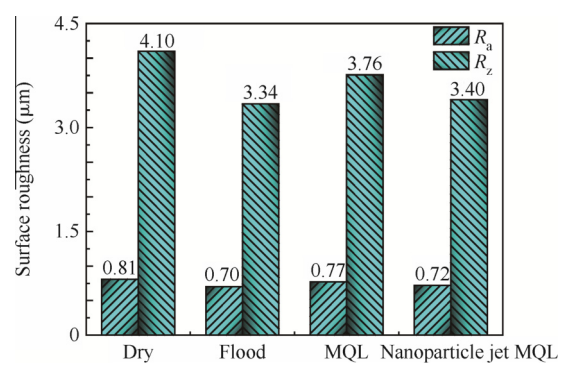


Fig. 7 Comparison of surface roughness under the four cooling lubrication approaches.

5.2. Analysis of results from Experiment 2

In this study, we further studied the lubrication performance of nanoparticle jet MQL. Given that different nanoparticle additives have different effects on grinding fluid lubrication performance, MoS_2, CNT, and ZrO_2 nanoparticles were used to prepare grinding fluids with similar base oil for grinding experiment. The YDM-III 99 three-dimensional dynamometer was used to measure the grinding force, as shown in Fig. 8.

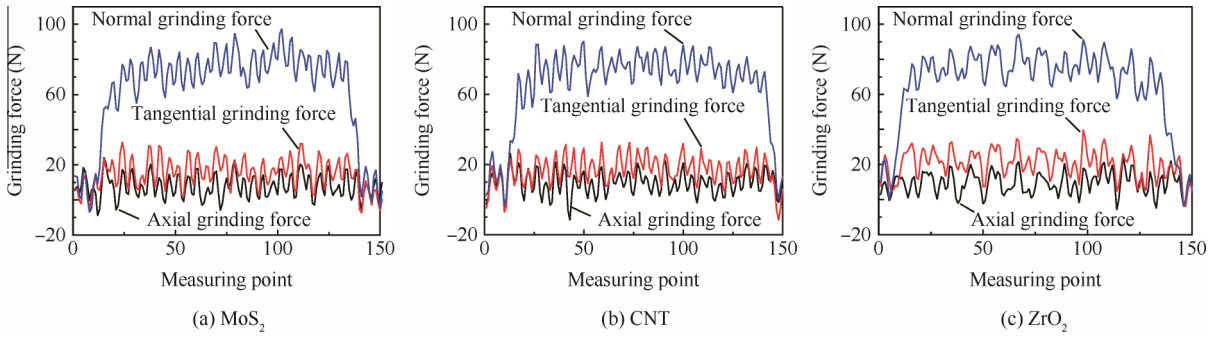


Fig. 8 Grinding force measured in the experiment.

The three nanoparticle jet MQL experiments using grinding fluids with MoS_2, CNT, and ZrO_2 nanoparticles generated small grinding forces with small differences, as shown in Fig. 8. The grinding forces at the stable condition of grinding were also measured. The frictional coefficients on the grinding surface, which was obtained as the ratio between the tangential and normal grinding forces, were 0.23, 0.247, and 0.258 respectively, with MoS_2, CNT, and ZrO_2 nanoparticle jet MQL grinding, as shown in Fig. 9(a).

The frictional coefficient in MoS_2 nanoparticle jet MQL was smaller than that in CNT and ZrO_2 nanoparticle jet MQL. This finding indicates the positive role of MoS_2 nanoparticle in lubricating the grinding surface. The average tangential grinding forces in MoS_2, CNT, and ZrO_2 nanoparticle jet MQL at a stable state of grinding were 19, 20.7, and 21.2 N, respectively. The tangential grinding forces were substituted into Eq. (1), and the specific grinding energies were calculated (Fig. 9(b)).

The tangential grinding force and the specific grinding energy in MoS_2 nanoparticle jet MQL were considerably lower than those of CNT and ZrO_2 nanoparticle jet MQL, as shown in Figs. 8 and 9. The tangential grinding forces of MoS_2, CNT, and ZrO_2 nanoparticle jet MQL were 32.7, 35.63, 36.49 J/mm^3. The grinding energies of MoS_2 nanoparticle jet MQL was smaller than those of CNT and ZrO_2 by 8.22% and 10.39%, respectively. This result suggests that the grinding power was reduced and lubrication performance on the grinding surface was greatly improved after adding MoS_2 nanoparticle in the grinding fluid. The smallest frictional coefficient was also obtained in MoS_2 nanoparticle MQL (0.23), which indicated its remarkable friction reducing effects. Its hierarchical structure also reduced the grinding force during grinding. MoS_2 appeared to be affected by the high temperature on the grinding surface and formed MoO_3 oxide film through oxidization, resulting in friction resistance.[52] The workpiece surface topographies (Fig. 10) were obtained after the friction experiments.

The workpiece surface topographies under three nanoparticle jet MQL conditions were uniformly smooth, without excessive material accumulation and adhesion. This finding verified the satisfactory lubricating performance and remarkable workpiece surface quality under nanoparticle jet MQL. By careful comparison, the workpiece surface quality in Fig. 10(a), which exhibited clear and structured surface texture, was better than those in Fig. 10(b) and (c). Certain material accumulations were observed in Fig. 10(b) and (c).

Moreover, the surface texture clearance and wave peak height were large. Surface profile measurements revealed the surface roughness of the workpieces under the three types of nanoparticle jet MQL (see Fig. 11).

The R_a and R_z values under the three nanoparticle jet MQL conditions did not present significant differences (Fig. 11). The R_a values in MoS_2, CNT, and ZrO_2 nanoparticle MQL grinding were 0.72, 0.737, 0.742 μm, with standard deviations of 0.031, 0.038, and 0.043 μm, respectively. The R_z values in MoS_2, CNT, and ZrO_2 nanoparticle MQL grinding were 3.4, 3.424, 3.505 μm, with standard deviation S of 0.115, 0.152, 0.183 μm, respectively. The roughness value in MoS_2 nanoparticle jet MQL condition was slightly smaller, which indicated that the workpiece surface quality was satisfactory under

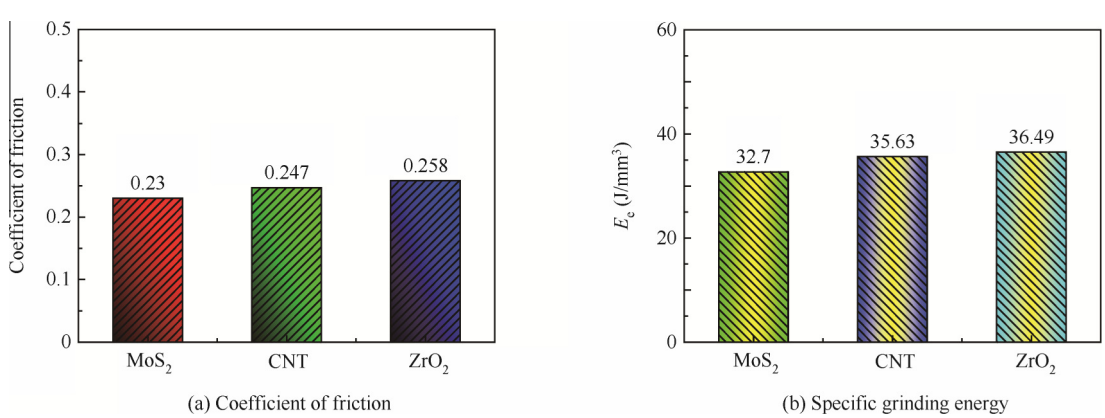
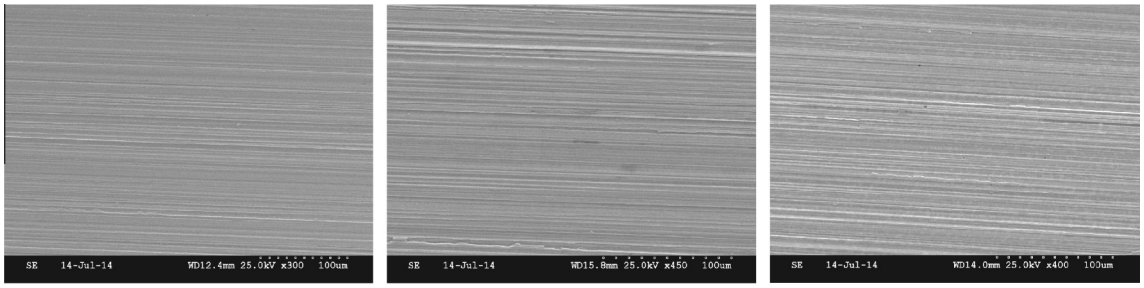


Fig. 9 Coefficient of friction and specific grinding energies in the three nanoparticle jet MQL conditions.



(a) MoS_2 (b) CNT (c) ZrO_2

Fig. 10 Surface topography of workpieces under the three nanoparticle jet MQL conditions.

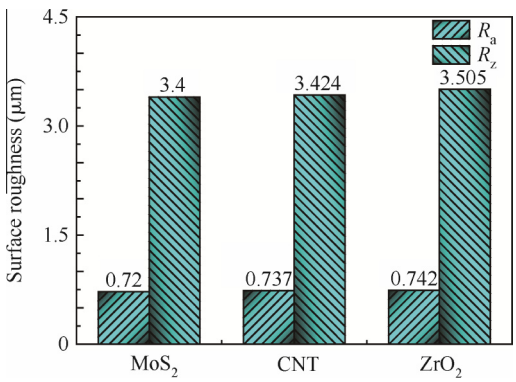


Fig. 11 Comparison on surface roughness under the three types of nanoparticle MQL.

MoS_2 nanoparticle jet MQL condition. The specific grinding energy and workpiece surface quality under the three types of nanoparticle jet MQL conditions were measured (Figs. 8 and 9(a)), and the best lubrication performance was observed in MoS_2 nanoparticle jet MQL.

5.3. Analysis of results from the three experiments

Based on the results of Experiments 1 and 2, the best lubrication performance of nanoparticle jet MQL grinding was obtained with MoS_2 nanoparticle as grinding fluid additive. Therefore, further research was conducted to identify the effect of different MoS_2 nanoparticle volume concentrations on the grinding fluid lubrication performance. Nanoparticle volume concentrations of 1%, 2%, and 3% were mixed in the grinding fluids with the base oil in the grinding fluid for our grinding experiments. The YDM-III 99 three-dimensional dynamometer was used to detect the grinding force in the stable state of grinding process, as shown in Table 5. The ratio of the tangential and the normal grinding forces was calculated to obtain the frictional coefficient on the grinding surface. The frictional coefficients obtained in MoS_2 nanoparticle MQL with three concentrations were compared (Fig. 12(a)).

Table 5 Tangential grinding force.

Volume concentration (%)	1	2	3
F_t (N)	19	18	22

Different frictional coefficients on the grinding surface were obtained with the different nanoparticles. The experimental results showed that the frictional coefficient was relatively small with a 2% nanoparticle volume concentration (0.22). By contrast, the frictional coefficients obtained from 1% and 3%, volume concentrations were larger than 2%. As nanoparticle volume concentration increased, frictional coefficient also increased and then declined, which indicated the influence of nanoparticle concentrations on lubricating the grinding surface. The data in Table 5 were substituted into Eq. (1), and the power consumption and lubrication conditions on the grinding surface with the grinding fluid containing MoS_2 nanoparticle at three volume concentrations were calculated. The calculated specific grinding energies E_e are shown in Fig. 12(b).

The specific grinding energy decreased and then increased as nanoparticle volume concentration increased from 1% to 2% and from 2% to 3%, respectively, as shown in Fig. 12(b). However, the specific grinding energy did not increase when the nanoparticle volume concentration increased from 1% to 3%. Therefore, the consumed grinding power is affected by nanoparticle volume concentration. Moreover, the lubrication condition on the grinding surface initially decreased and then increased as volume concentration increased. MoS_2 nanoparticle demonstrated better lubrication performance with 2% volume concentration than with 1% and 3% volume concentrations. The trends of R_a and R_z values after the grinding experiment with different MoS_2 nanoparticle volume concentrations are illustrated in Fig. 13.

The R_a and R_z values presented identical trends, in which they initially decreased and then increased, as MoS_2 nanoparticle volume concentration increased, as shown in Fig. 13. R_a value and R_z values decreased from 0.72 and 3.4 μm to 0.71 and 3.36 μm, respectively, as MoS_2 nanoparticle volume concentration increased from 1% to 2%. The values continued to increase as the nanoparticle volume concentration increased. The R_a and R_z values increased from 0.71, 3.36 μm to 0.74 and 3.48 μm, respectively, as MoS_2 nanoparticle volume concentration increased from 2% to 3%. The standard deviation S of R_a and R_z values under 1%, 2%, 3% MoS_2 nanoparticle volume concentrations were 0.031, 0.017, and 0.037 μm and 0.115, 0.087, 0.146 μm, respectively. These results are mainly attributed to the anti-wear and friction reducing performance of MoS_2 nanoparticle at increasing volume concentration, which improved the lubrication

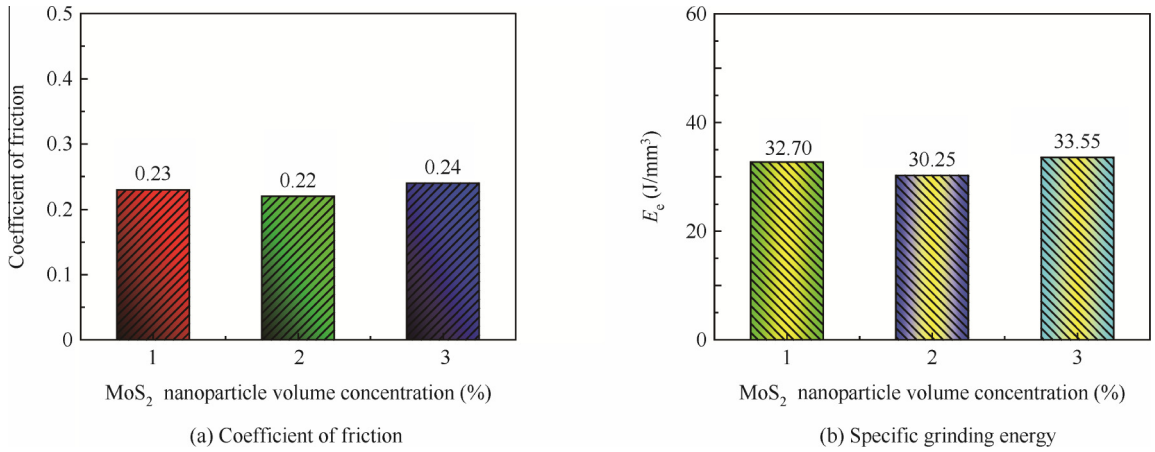


Fig. 12 Coefficient of friction and specific grinding energy under the three volume concentrations of MoS_2 nanoparticle.

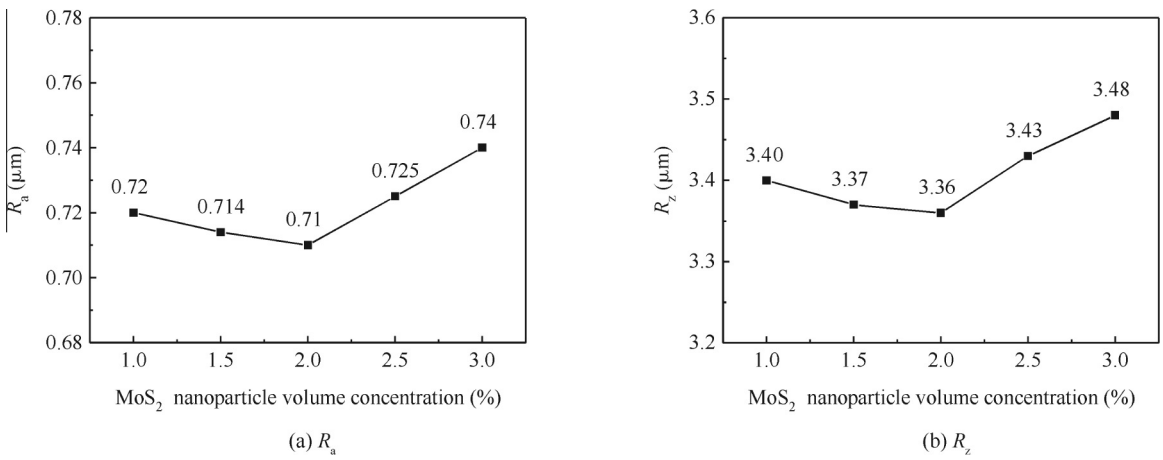


Fig. 13 Surface roughness under the three MoS_2 nanoparticle volume concentrations of R_a and R_z.

performance of the grinding surface. Under this circumstance, nanoparticles tended to cluster. Moreover, large frictional coefficient is indicative of small lubrication performance. Hence, at 2% MoS_2 nanoparticle volume concentration, the surface roughness R_a and R_z values were small, which indicated satisfactory surface quality.

6. Conclusions

Given the results in Experiments 1, 2, and 3 on the four cooling lubrication conditions (dry grinding, flood, MQL, and nanoparticle jet MQL), their lubrication performance during grinding was compared. Results from the grinding force, frictional coefficient, specific grinding energy, and the surface roughness verified the lubrication performance of nanoparticle jet MQL.

Further studies on nanoparticle jet MQL were also conducted. MoS_2, CNT, and ZrO_2 nanoparticles were used as grinding fluid additives for the grinding experiments. A comparison of the specific grinding energies and the surface roughness values of the three nanoparticles showed that the specific grinding energy in MoS_2 nanoparticle jet MQL was 32.7 J/mm^3, which was 8.22% and 10.39% lower than that of the other two nanoparticles. MoS_2 nanoparticle jet MQL also generated the optimal surface quality. Hence, MoS_2 nanoparticle presented the optimal lubrication performance among the three types of nanoparticles.

The effects of 1%, 2%, and 3% MoS_2 nanoparticle volume concentrations on lubrication performance and surface quality were also investigated. The grinding forces and surface topographies were analyzed using the frictional coefficients, the specific grinding energies, and the surface roughness values. The analysis showed that the grinding surface lubrication performance was influenced by MoS_2 nanoparticle volume concentration. The best lubrication performance and the optimal workpiece surface quality were obtained with 2% MoS_2 nanoparticle volume concentration.

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