Theory analysis of grinding fluid jet and its effect on surface roughness of workpiece

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Abstract: In grinding process, a small amount of grinding fluid can be injected into the contact area for cooling and lubrication. This leads to decrease of the grinding fluid utilisation efficiency and workpiece surface integrity. Based on fluid mechanics theory, a mathematical model of two-phase flow field is established and the simulation of the grinding fluid jet is carried out by FLUENT. The distribution of grinding fluid and the pressure variation curve of the jet process are obtained. The results show that less utilisation efficiency of the grinding fluid in contact area is a combined effect of high pressure airflow, severe backflow and large pressure difference. The utilisation efficiency of the grinding fluid can be improved when jet occurs at the middle position with higher velocity. In addition, in the grinding experiment of surface roughness, the suitable supply parameters are proved by analysing Ra values of the parts.

Keywords: grinding fluid; jet; two-phase flow; simulation; surface roughness; supply parameters.


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1 Introduction

Grinding fluid has the function of lubrication, cooling and cleaning in grinding, widely employed in conventional machining operations and abrasive processes. The effective supply of grinding fluid can improve the surface roughness of the workpiece, prevent excessive grinding temperatures and extend the life of the grinding wheel. However, the fluid waste always occurs because the useful supply flow fails to reach the contact area. This often results in lower utilisation efficiency of grinding fluid. It is means that not only the economic losses, but also the environmental pollution must be considered in grinding processes (Jovane et al., 2008; Zhang et al., 2015). Therefore, it is crucial to study features and regularity of grinding fluid jet process, in order to choose suitable supply parameters for improving surface roughness of workpiece, and increase the green degree of the grinding process.

Many researchers have found various useful methods to obtain suitable supply parameters. The paper compared the grain size of the wheel, and obtained the experiment result that the depth of grinding fluid penetration was usually small. This result indicated that the grinding fluid remained mainly on the surface of the wheel and did not flow deeply into the pores of the wheel (Gviniashvili et al., 2004). The work reviewed application methods of reducing the consumption of the grinding fluid in the grinding process. The approaches leading to the reduction of grinding fluid mainly were discussed, and the influence of nozzle positioning and geometry were significant to the useful flow rate in the contact area (Irani et al., 2005). Another paper showed the quantity of fluid depended on grinding ways and the method of application. Results from this research suggested that supply flow rate needed to be four times the achievable ‘useful’ flow rate. Extra flow rate was wasted. Improved system design allowed ‘actual’ useful flow rate to approach ‘achievable’ useful flow rate. Achievable useful flow rate depended on wheel porosity and wheel speed whereas actual useful flow rate depended on nozzle position, design, flow rate and velocity (Morgan et al., 2008). The work presented two approaches aiming at the optimisation of fluid application in grinding. First, the influence of nozzle design on the development of velocity and pressure fields was studied using CFD tools. Second, a grinding technology that combined MQL with low-temperature CO2 was discussed (Alberdi et al., 2011). Recently, minimum coolant grinding (MCG) process was concerned. The minimum quantity of lubricant-low temperature gas grinding technology only required minimisation of both gas and oil consumption. Experimental results showed that even with very low quantities of oil and gas (3 mL/min and 0.2 kg/min), the MCG process produced better results than conventional cooling in terms of specific grinding energy and wheel wear. Moreover, the amount of oil could be greatly reduced if effective freezing was achieved (Garcia et al., 2013). This paper made an investigation on using TRIM E709 emulsifier with Al2O3 nanoparticles to reduce the heat generated at grinding zone. An experimental setup had been developed and detailed comparison had been done in terms of temperature distribution and surface finish, based on TRIM E709 emulsifier and TRIM E709 emulsifier with Al2O3 nanoparticles in grinding EN-31 steel. Results showed that surface roughness and heat penetration were decreased with addition of Al2O3 nanoparticles (Vasu and Manoj, 2011). To reduce the usage of grinding fluid, nanofluid had recently been applied to grinding process with minimum quantity lubrication (MQL) technique. In this study, surface grinding of
hardened AISI 52100 steel under different spraying parameters was carried out. Experimental results showed with jet velocity increasing that the MQL nozzle spraying direction had important effects on the application of the nanofluid mist. Grinding forces, surface roughness, and grinding temperature were decreased with the increase of air pressure, and grinding performance in shorter spraying distance was better than that in longer spraying distance (Mao et al., 2013).

Although there are many studies on the grinding fluid supply parameters, it is not very clear about the features and regularity of grinding fluid jet. The purposes of this paper is to study the motion rules of the grinding fluid jet process based on the two-phase flow theory, analyse the influence factors on the grinding fluid utilisation efficiency, and obtain suitable supply parameters of grinding fluid jet.

This paper has been organised as follows. In Section 2, the theory analysis of grinding fluid jet is performed, and the mathematic model of the two-phase flow field is built. In Section 3, the simulation model is built with VOF method, and the simulation experiment is carried out. The distribution figure of the grinding fluid and the pressure curve are compared at the different nozzle positions and jet velocity. The simulation results show the main reason for the less efficiency of the grinding fluid in grinding process. Furthermore, it is found that an optimal grinding performance depend on the jet position and the jet velocity. In Section 4, the grinding experiment of surface roughness affected by supply parameters of grinding fluid is carried out. The Ra values of the parts are measured by 3D surface measurement instrument. The results present that the jet position and nozzle flow rate have a significant impact on surface roughness of parts. In Section 5, the conclusions of this paper are discussed.

2 Theory analysis of grinding fluid jet

2.1 Grinding gas-liquid two-phase flow

In the grinding process, due to the grinding wheel rotating with high velocity, an air boundary layer can create around the grinding wheel and prevent the grinding fluid from entering effectively into contact area (Guo and Malkin, 1992; Brinksmeier et al., 1999; Li and Han, 2013). The air boundary layer is mainly composed of circulation and radial flow. The circulation is formed by rotating air along the circumference of rotating wheel; the radial flow is formed by the air drawn into the contact area along the grinding wheel surface (Schumack et al., 1991; Zhang and Nakajima, 2000; Han and Li, 2013). To obtain enough supply of grinding fluid, it is necessary to overcome these adverse effects of airflow.

Under the influence of air boundary layer, the jetted grinding fluid can be mainly divided into three parts. Part one of grinding fluid is drawn into grinding wheel pinhole by capillary action, and is used as the coolant for the grinding wheel. Part two of grinding fluid breaks through the air layer around the grinding wheel, directly flowing into the contact area. It can reduce grinding heat and clean the abrasive dust. Part three of grinding fluid is blocked by high-pressure airflow, turning into the spray to be evaporated or thrown out. It results in the loss of grinding fluid and environmental pollution (Brinksmeier et al., 2006; Murzyn et al., 2007; Ebbrell et al., 2000). Therefore, it is very necessary to study the whole jet process to improve the utilisation efficiency of grinding fluid.
According to the above analysis, in the process of jetting, grinding fluid interacts with the air violently in the contact area, forming a complex flow field between the wheel and the workpiece, as shown in Figure 1. To the study of grinding fluid jet process, the assumption is appropriate that the movement of the fluid in contact area should be the multiphase flow. It is defined as the grinding gas-liquid two-phase flow in this paper. Gas phase and liquid phase can be considered as continuous mediums respectively, and fill the whole grinding contact area simultaneously. When the flow parameters of each phase on the phase interface are discrete, the interface shape and distribution of the gas-liquid two-phase change with the flow process. There is the interaction of mass, momentum and energy among phases on the interface, besides the interior of each phase. Due to the density difference and the different inertia of gas-liquid two-phase flow, the flow process is extremely complicated, fluid motion should be regarded as the turbulent flow, and the mathematical model of gas-liquid two-phase flow should be transient model (Hryniewicz et al., 2001).

Figure 1  Gas-liquid flow field

2.2 Mathematical model of grinding fluid jet

According to the theory of fluid mechanics, the following equations of fluid flow are used to describe transient model of grinding fluid jet process:

The continuity equation can be expressed as:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]

(1)

where \( \rho \) – fluid density; \( t \) – time; \( u \) – velocity component along x axis; \( v \) – velocity component along the y axis; \( w \) – velocity component along the z axis.
Theory analysis of grinding fluid jet and its effect on surface roughness

The momentum conservation equation can be expressed as:

\[
\rho \frac{du}{dt} = \rho F_x = \frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left( \mu \frac{\partial u}{\partial x} + \frac{\partial}{\partial y} \left( \frac{\partial u}{\partial y} + \mu \right) + \frac{\partial}{\partial z} \left( \frac{\partial u}{\partial z} + \mu \right) \right) + \frac{\partial}{\partial x} \left[ \mu \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) \right]
\]

(2)

\[
\rho \frac{dv}{dt} = \rho F_y = \frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left( \mu \frac{\partial v}{\partial x} + \frac{\partial}{\partial y} \left( \frac{\partial v}{\partial y} + \mu \right) + \frac{\partial}{\partial z} \left( \frac{\partial v}{\partial z} + \mu \right) \right) + \frac{\partial}{\partial y} \left[ \mu \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) \right]
\]

(3)

\[
\rho \frac{dv}{dt} = \rho F_z = \frac{\partial p}{\partial z} + \frac{\partial}{\partial x} \left( \mu \frac{\partial w}{\partial x} + \frac{\partial}{\partial y} \left( \frac{\partial w}{\partial y} + \mu \right) + \frac{\partial}{\partial z} \left( \frac{\partial w}{\partial z} + \mu \right) \right) + \frac{\partial}{\partial z} \left[ \mu \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) \right]
\]

(4)

where \( F_x \) – Reynolds stresses component along \( x \) axis; \( F_y \) – Reynolds stresses component along \( y \) axis; \( F_z \) – Reynolds stresses component along \( z \) axis; \( p \) – the pressure on micro unit; \( \mu \) – dynamic viscosity of the fluid.

The energy conservation equation can be expressed as:

\[
C_p \frac{dT}{dt} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + \phi
\]

(5)

where \( C \) – specific heat capacity of micro unit; \( \rho \) – density of micro unit; \( T \) – temperature of micro unit; \( \lambda \) – thermal conductivity; \( \phi \) – sum of viscous dissipation.

In order to specify the fluid motion of the turbulent flow with the above equations, turbulent transfer equation should be supplemented. At present, standard \( k - \varepsilon \) model (turbulent kinetic energy \( k \) equation and turbulent dissipation rate \( \varepsilon \) equation) is the most widely applied turbulent transfer equation (Kataoka and Serizawa, 1989). When standard \( k - \varepsilon \) model is used to calculate strong vortex, filament line or curved surface streamline flow, the normal stress may transform from positive stress to negative stress, and this transform can result to distortion (Versteeg and Malalasekera, 1995). Therefore, in order to compensate for this defect, standard \( k - \varepsilon \) model is revised by constraining normal stress. Realisable \( k - \varepsilon \) equation is one of improved equations that are widely used. In this paper, unlike previous jet simulation studies which use standard \( k - \varepsilon \) equation, Realisable \( k - \varepsilon \) equation is adopted in grinding gas-liquid two-phase field simulation.

Realisable \( k - \varepsilon \) turbulent flow transport equation can be expressed as:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_j k)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \frac{\mu + \mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \varepsilon
\]

(6)

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_j \varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \frac{\mu + \mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_1 \varepsilon \frac{k}{\varepsilon} - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\varepsilon} \sigma_e}
\]

(7)

where \( C_1, C_2, \sigma_\varepsilon, \sigma_k \) – model constants respectively; \( k \) – turbulent kinetic energy; \( \mu \) – kinetic viscosity; \( \mu_t \) – turbulent flow kinetic viscosity; \( u_j \) – mean velocity; \( G_k \) – turbulent kinetic energy production caused by mean velocity gradient; \( \nu \) – molecular kinematic viscosity; \( E \) – scalar measure of the deformation tensor; \( \varepsilon \) – turbulent dissipation rate.
The model constants have the following default values:

\[ C_1 = \max \left( \frac{0.43}{\eta + 5}, 1.9, \sigma_k = 1.0, \sigma_e = 1.2 \right), \]

\[ \eta = \left( 2E_{ij} \cdot E_{jk} \right)^{1/2} \frac{k}{\sigma}, E_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \]

\[ \mu_i \text{ is computed from:} \]

\[ \mu_i = \rho C_\mu \frac{k^2}{\sigma} \]  

(8)

\[ C_\mu \text{ is computed from:} \]

\[ C_\mu = \frac{1}{A_0 + A_s U^* k / \sigma} \]  

(9)

The model constants \( A_0 \) and \( A_s \) are given by:

\[ A_0 = 4.0, \quad A_s = \sqrt{6} \cos \phi, \quad \phi = \frac{1}{3} \cos^{-1} \left( \sqrt{6W} \right), \quad W = \frac{E_{ij}E_{ik}E_{jk}}{\left( E_{ij}E_{ij} \right)^{1/2}}, \]

\[ U^* = \sqrt{E_{ij}E_{ij} + \Omega_{ij} \Omega_{ij}}, \quad \Omega_{ij} = \Omega_{ij} - 2\epsilon_{ijk}\Omega_{kj}, \quad \Omega_{ij} = \overline{\Omega}_{ij} - \epsilon_{ijk}\omega_k. \]

where \( \Omega_{ij} \) – mean rate-of-rotation tensor viewed in a rotating reference frame with the angular velocity; \( \omega_k \) – angular velocity; \( E_{ij} \) – mean strain rate; \( \epsilon_{ijk} \) – viscosity dissipative term; \( \overline{\Omega}_{ij} \) – mean rotation rate tensor.

3 Simulation of grinding fluid jet

3.1 VOF method

At present, there are two main numerical simulation methods of describing gas-liquid two-phase flow: the Eulerian-Eulerian method and the Eulerian-Lagrange method. Eulerian-Lagrangian method integrates the position change of all fluid particles with time to study the movement of the whole fluid field. This method is very intuitive, but difficult to achieve (Ji and Shi, 2008). In Eulerian-Eulerian method, the flow field filled with space point is regarded as the research object; ignore individual fluid particle motion process, focus on all the time the change rule of the space point in the flow field. In FLUENT, there are three types of Eulerian-Eulerian multiphase flow model: volume of fluid (VOF) model, mixture model, and Eulerian model.

VOF model is an effective method for processing the flow patterns change between several incompatible fluids on the surface of fixed Eulerian grid. In the VOF model, the same set of momentum equations is shared by different fluids. VOF model simulates the movement of multiple incompatible fluids by solving the volume fraction of each fluid in flow field (Gao et al., 2003).
This paper adopts the VOF method to simulate the jetting process of grinding fluid. The movement rules of grinding fluid in the contact area are mastered by tracking the change of the grinding fluid volume fraction. By the analyses of utilisation efficiency of grinding fluid, the suitable supply parameters are studied.

3.2 Establishment of simulation model

At the bottom of grinding wheel surface, a wedge-shape flow field infinitesimal was selected as the study object. Set the radial normal direction of the grinding wheel as Y-axis direction and the tangential direction as the X-axis direction. A 2D gas-liquid two-phase flow field model is established, as shown in Figure 2.

Figure 2  Model of flow field

The quality of the mesh was significant important in the accuracy and stability of the numerical computation (Nakayama and Shibata, 1998). Finite element meshing was performed by the pre-processing package GAMBIT. In order to obtain the required accuracy efficiently, the element meshing operation was as follows: the model was meshed in accordance with the first edge and then faces the order; local refinements need be carried out on the grinding wheel surface; mesh ratio should be appropriately increased near the minimum clearance.

Figure 3  Boundary condition of the meshing model (see online version for colours)
Various boundary conditions of this model are set as follows in FLUENT: velocity-inlet boundary, pressure-inlet boundary and wall boundary (Fluent Inc., 2012). The velocity-inlet and the pressure-inlet are set to normal atmospheric pressure, the workpiece surface was defined as stationary wall boundary, and grinding wheel surface was defined as moving wall. The boundary condition of the meshing model is shown in Figure 3.

The simulation parameters of grinding fluid jet process were set, shown as Table 1. Vertical distance of jet was vertical height between nozzle and workpiece. The vertical distance of middle position was 5 mm, and the bottom position was 10 mm. In addition, the following simplifications and assumptions were conducted: environmental pressure was normal atmospheric pressure; the influence of the pressure and temperature on fluid viscosity can be ignored.

Table 1  Simulation parameters

<table>
<thead>
<tr>
<th>Item</th>
<th>Values</th>
</tr>
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<tbody>
<tr>
<td>Grinding wheel diameter (mm)</td>
<td>200</td>
</tr>
<tr>
<td>Angular velocity of grinding wheel (rad/s)</td>
<td>200</td>
</tr>
<tr>
<td>Minimum clearance (mm)</td>
<td>0.1</td>
</tr>
<tr>
<td>Jet velocity (m/s)</td>
<td>6/11</td>
</tr>
<tr>
<td>Grinding fluid density (kg/m³)</td>
<td>1000</td>
</tr>
<tr>
<td>Grinding fluid dynamic viscosity (Pa·s)</td>
<td>0.05</td>
</tr>
<tr>
<td>Air density (kg/m³)</td>
<td>1.2</td>
</tr>
<tr>
<td>Air dynamic viscosity (Pa·s)</td>
<td>1.8e-5</td>
</tr>
<tr>
<td>Horizontal distance of jet (mm)</td>
<td>40</td>
</tr>
<tr>
<td>Vertical distance of jet (mm)</td>
<td>Middle/bottom</td>
</tr>
</tbody>
</table>

3.3 Analysis of simulation results

There were four simulate experiments were performed in this section. The specific experiment arrangement was shown as Table 2.

Table 2  Experimental arrangement

<table>
<thead>
<tr>
<th>Item</th>
<th>Content</th>
</tr>
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<tbody>
<tr>
<td>No.</td>
<td>1</td>
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<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Jet velocity (m/s)</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Nozzle position</td>
<td>Middle</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
</tr>
</tbody>
</table>

The simulation process was described below. After boundary conditions were set, the iteration of the flow field was continued until the model converged. By tracking the variational volume fraction and pressure of grinding fluid in contact area, the analyses results were obtained.

When the jet velocity was 11 m/s, at the middle position and the bottom position respectively, the distribution of the grinding fluid were shown as Figure 4.
Because the peripheral velocity of grinding wheel was faster than the jet velocity of grinding fluid, grinding wheel drove the air into the interface between the grinding wheel and the grinding fluid, resulting in grinding fluid in the contact area accelerated. Some grinding fluid cannot break through the air barrier and was sprayed from the contact area under the action of air resistance. As a result, this part of grinding fluid had no chance to enter into the contact area; the remainder would break through the air barrier and move toward the minimum clearance. The distribution of grinding fluid at this moment was shown in Figure 4(a).
When grinding fluid approached the high pressure contact area, high-velocity rotary airflow made the energy loss of the grinding fluid increased, and then the phenomenon of the backflow appeared. Eventually, the grinding fluid was full of the minimum clearance, shown as Figure 4(b). This can produce very good cooling and lubricating effect.

In Figure 4(c), the grinding fluid in the high pressure area hit the grinding wheel, and was drawn into the contact area by the grinding wheel. Under the action of air boundary layer, the severe turbulence was formed and the front of the grinding fluid bent downward in the periphery of the contact area. Comparing Figure 4(c) with Figure 4(a), it can be shown that jetting grinding fluid at the bottom meets hindrance and backflow more seriously. With the movement of the grinding fluid, the minimum clearance was not full of grinding fluid in the end, this indicated that the grinding fluid supply was inadequate; utilisation efficiency of grinding fluid at bottom position became worse than at middle position, shown as Figure 4(d).

The jet movement process of grinding fluid at the middle position was demonstrated in Figures 5(a) and 5(b), at the bottom position demonstrated in Figures 5(c) and 5(d).

In Figures 5(a) and 5(c), the backflow of the grinding fluid occurred. It proved that the turbulence was formed in contact area. By contrast with Figure 5(b), Figure 5(d) showed a large number of grinding fluid was speeding up to leave the contact area, utilisation efficiency of grinding fluid became poor when the grinding fluid jet at the bottom position. This conclusion accorded quit well with the analysis to Figure 4.

By comparing Figure 4 with Figure 5, grinding fluid with higher jet velocity obtained more kinetic energy to break through the air boundary layer. Therefore, utilisation efficiency of grinding fluid improved in contact area.

**Figure 5** Distribution of grinding fluid at 6 m/s jet velocity, (a) in the jetting initial phase at middle position (b) in the jetting later phase at middle position (c) in the jetting initial phase at bottom position (d) in the jetting later phase at bottom position (see online version for colours)
Figure 5  Distribution of grinding fluid at 6 m/s jet velocity, (a) in the jetting initial phase at middle position (b) in the jetting later phase at middle position (c) in the jetting initial phase at bottom position (d) in the jetting later phase at bottom position (see online version for colours) (continued)

Figure 6  Pressure diagram in contact area, (a) at bottom position (b) at middle position (see online version for colours)

Under different jet velocities, the pressure characteristics of the flow field were studied. At bottom position, jet velocities were respectively 6 m/s and 11 m/s, the maximum pressure values were respectively 10 kPa and 19 kPa, the minimum pressure values were respectively –1.5 kPa and –4.5 kPa near the minimum clearance position. Pressure value
along the X axis direction changed from zero to a negative, was increased till the peak appeared, and finally reduced to 0, shown as Figure 6(a).

At middle position, jet velocities were respectively of 6 m/s and 11 m/s, the maximum pressure values were respectively 18 kPa and 62 kPa, the minimum pressure values were respectively –1.5 kPa and –6 kPa near the minimum clearance position, shown as Figure 6(b).

With comparing the above curves, it can be seen that the highest pressure values of the flow field appeared at position (X-direction) about from 18 to 20 mm while jetting at the bottom position, and from 12 to 16 mm at the middle position. And near the minimum clearance position the positive pressure values became negative, forming a negative pressure zone. When the jet position was set, the maximum pressure value at 11 m/s jet velocity was significantly higher than at 6 m/s, the minimum pressure value was smaller accordingly. In contact area, increasing the pressure difference was advantageous for the grinding fluid injection Therefore, it can be inferred that grinding fluid supply was sufficient at 11 m/s jet velocity.

By comprehensive comparing the above four simulate experiments, the conclusion can be drawn:

1. When grinding fluid was injected into the contact area, there was complex interactions between grinding fluid and air barrier, the turbulence and backflow occurred with great loss of energy and the pressure changed drastically. All these result in the utilisation efficiency of grinding fluid was low.

2. When the grinding fluid jet velocity was set, the useful flow rate at middle position was more than at bottom position.

3. When the jet position was set, the useful flow rate increased with increasing jet velocity of grinding fluid.

4. **Experiment of surface roughness affected by supply parameters**

4.1 **Experiment design**

Due to plastic deformation, brittle fracture and vibration in the process of cutting, the workpiece surface can leave microstructure with different shapes and sizes. This surface microstructure is usually described by surface roughness. Surface roughness is microcosmic error of geometrical shape on the machined surface. It has great effect on the fit accuracy, fatigue strength, wear resistance, and sealing performance of the workpiece. It is also one of the important indexes to evaluate the surface integrity of the machine workpiece and products (Xiu et al., 2014; Rogelio and Steven, 2003).

Due to infiltrating abrasive particles and workpiece, grinding fluid can form lubricant film and adhere to the surface. This can reduce the surface roughness and friction between the abrasive grain and parts (Rowe et al., 1995; Ramesh et al., 2004). Therefore, the surface roughness of machined workpiece is decreased by reasonably choosing grinding fluid supply parameters. In this paper, the arithmetical mean deviation (Ra) of the profile is measured to verify the reasonableness of the grinding fluid supply parameters.
In the grinding experiment, STIL CHR150 three-dimensional surface measurement instrument is used to measure Ra. This instrument can be used to measure the surface roughness value of parts, which dedicated to high resolution 3D microtopography and texture analysis. STIL CHR150 3D surface measurement instrument is shown in Figure 7.

The grinding experiment with 45 steel parts was carried out on a M7130 surface grinding machine, and the grinding wheel’s type was WA60. The nozzle was placed in two different locations, the bottom position and the middle position, with the same definition of position in the Section 3.2. The arrangement of the grinding experiment was shown as Table 3.

<table>
<thead>
<tr>
<th>Item</th>
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<tbody>
<tr>
<td>Parts no.</td>
<td>1 2 3 4</td>
</tr>
<tr>
<td>Grinding fluid nozzle flow rate (L/min)</td>
<td>3 3 7 7</td>
</tr>
<tr>
<td>Nozzle position</td>
<td>Bottom Middle Bottom Middle</td>
</tr>
</tbody>
</table>

4.2 Experimental results and discussion

After the surface roughness was measured and calculated by the 3D surface measurement instrument, the 3D surface topography of parts 1 was shown in Figure 8. The Ra values of the parts were shown in Figure 9.

It can be seen from Figure 8 that the values of Ra were 2.9, 2.5, 2.7 and 2.1 respectively from parts 1 to parts 4. The Ra value of parts 1 was the biggest, and the Ra value of parts 4 was the smallest. This indicated that the cleanliness of parts 1 was worst, namely, the effective amount of grinding fluid was the least in the contact area during grinding process. On the contrary, to parts 4, the effective amount of grinding fluid was the most.
By analysing the change trend of the surface roughness Ra value, the results can be obtained as follows:

1. When the jet position was set, the Ra value of parts surface decreased with the increase of grinding fluid nozzle flow rate. It indicated that increasing the flow rate of grinding fluid can significantly improve the surface roughness of the parts. Plenty of grinding fluid can transfer the grinding heat, lower the temperature, and slow down the plastic deformation on the parts surface.

2. When the jet flow rate of grinding fluid was set, the Ra value of parts was smaller at the middle position than at the bottom position. It means there was more useful flow rate of grinding fluids at the middle position, and improved the surface roughness of workpiece.

Figure 8  3D surface topography of parts 1 (see online version for colours)

Figure 9  Ra values of the parts (see online version for colours)
5 Conclusions

In order to improve the utilisation efficiency of the grinding fluid, the features and regularity of grinding fluid jet in contact area is studied, and the suitable supply parameters are discussed. The following conclusion can be drawn from the above studies.

1 The simulation of grinding gas-liquid two-phase flow model can preferably reflect the movement features of grinding fluid jet process. By observing the simulation process, the causes of the less utilisation efficiency of the grinding fluid are found. The high pressure airflow, the severe grinding fluid backflow and large pressure difference of flow field make grinding fluid lose a lot of energy. As a result, only a small amount of the grinding fluid can enter into the contact area.

2 Based on the analysis of the distribution figure of grinding fluid and the pressure variation curve, the simulation results present that the flow rate of useful grinding fluid can be influenced by nozzle position and jet velocity. When the grinding fluid jet velocity is set, the useful flow rate at middle position is much more than at bottom position. When the jet position is set, the useful flow rate increases with increasing jet velocity of grinding fluid.

3 According to the Ra values from surface roughness experiment, it can be find that the surface roughness of parts depends on nozzle position and nozzle flow rate. The surface roughness is better at middle jet position than at bottom jet position. Thus, the grinding fluid jet can achieve better effects at the middle position with more nozzle flow rate.

4 It is seen that the supplying parameters of the grinding fluid have noteworthy impact on the utilisation efficiency of grinding fluid and surface roughness of workpiece. By simulation study, the supply parameters can be reasonably chosen to reduce the amount of grinding fluids and improve the surface integrity of workpiece.

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