Investigation on the grinding temperature field of nano-ZrO$_2$ dental ceramics with a nanoparticle jet of MQL

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Abstract: The heat-transfer model of a surface grinding temperature field with a nanoparticle jet flow of minimum quantity lubrication (MQL), as well as the proportionality coefficient model of the energy input workpiece, was established. Numerical simulation of the surface grinding temperature field of a nano-ZrO$_2$ dental ceramic workpiece material was conducted. With increased cut depth, the peak values of grinding temperature rocketed. With increased workpiece feed speed, grinding temperature on the finished surface decreased. With increased wheel peripheral speed, a high amount of heat energy accumulated on the surface because of the low heat-transfer coefficient of the ceramic material, and a large temperature gradient appeared in the temperature distribution layer. Under the same cooling and lubrication conditions, grinding temperature insignificantly changed along the direction of grinding width. Conversely, under different cooling conditions, the temperature variation was significant. MQL grinding conditions with additive nanoparticles significantly affected the weakening of temperature effect on the grinding zone.

Keywords: grinding; temperature field; nano-ZrO$_2$ dental ceramics; nanoparticle jet; minimum quantity lubrication; MQL.


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grinding; superabrasive grinding wheels; grinding temperature field modelling; simulation of grinding processes; minimum quantity lubrication (MQL) grinding and high speed machining.

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1 Introduction

Minimum quantity lubrication (MQL) refers to the minimum quantity of lubricants that enters the high-temperature grinding zone after being mixed in high-pressure gas and atomised with high pressure draft (4.0–6.5 bar). The traditional flood cooling feed liquid of grinding fluid is 60 L/h for a unit of the width of grinding wheel, whereas the consumption of MQL grinding fluid is 30–100 ml/h for a unit of the width of the grinding wheel (Li et al., 2013; Kopac and Krajnik, 2006; Varghese et al., 2000). The high pressure draft functions in cooling and chip removal. Lubricants attach onto the finished surface of a workpiece, forming a layer of protective film and serving as lubrication (Brinksmeier et al., 2010; Wegener et al., 2011). This technology integrates the advantages of flood cooling grinding and dry grinding, presenting lubrication effects similar to those of traditional flood cooling grinding (Oliveira et al., 2009; Hadad and Sadeghi, 2012; Tawakoli et al., 2010; Kalita et al., 2012a). Lubricants adopt vegetable oil as the alkyl ester of base oil, which have the features of excellent biodegradability, good lubricating properties, high viscosity index, low volatility, recycling, short production cycle, and insignificant environmental diffusion. The consumption of lubricants is only parts per thousand or a few hundredths of a percentage point compared with traditional grinding approaches, which greatly improve the working environment. Thus, high pressure draft is an efficient low-carbon processing technology. However, studies show that the cooling effect of high pressure draft is too limited to meet the needs of strengthened high-temperature heat transfer of the grinding zone (Li et al., 2011a). The processing quality of the workpiece and grinding wheel life is poorer than that of traditional flood cooling grinding, indicating that MQL technique requires further improvements (Wang et al., 2013).
To improve the defects in the cooling effect of MQL grinding, the Sanchez (Sanchez et al., 2010; Shen et al., 2008) team from Spain applied low-temperature CO2 to MQL grinding, i.e., they injected low-temperature CO2 (238 K) and MQL medium with two nozzles into the grinding zone with a form of jet flow. Given the advantageous low-temperature heat-transfer property of CO2, the temperature of the grinding zone can be further reduced. Studies have shown that the consumption of CO2 is remarkable (40 L/min), and two sets of feeding systems are needed. The costs are high and the rapid volatile property of CO2 constrains its strengthened heat transfer in the grinding zone (low-temperature CO2 MQL grinding ratio $G = 4.5$; flood cooling lubrication grinding ratio $G = 4.22$). Hence, the cooling effect of cryogenic gas on improving MQL is subject to certain restrictions.

According to strengthened heat transfer theory, the heat-transfer ability of a solid greatly exceeds those of a liquid and a gas. At room temperature, the coefficient of thermal conductivity of solid materials is greater than that of a fluid material by several orders of magnitude. In Table 1, we compared the coefficient of thermal conductivity of solid with liquid materials (Barczak et al., 2010). The coefficient of thermal conductivity of liquid with suspended metal, non-metallic, or polymeric solid particles significantly exceeded that of pure liquid. If solid particles were added to MQL medium, a great increase in the coefficient of thermal conductivity of fluid medium would be expected. This increase improves convective heat transfer and offsets the defects of the insufficient cooling effects of MQL. In addition, nanoparticles (i.e., ultrafine tiny solid particles with at least one dimension in the three-dimensional space that is within the nanoscale range of 1–100 nm) also present tribological features such as special antifriction and high carrying capacity in the aspects of lubrication and tribology. In this research, we added nanoscale solid particles to MQL fluid medium to produce nanofluids. Specifically, we injected nanoscale solid particles after the mixing and atomisation of nanoparticles, lubricants (oil or oil-water mixture) and high-pressure gas in the grinding zone in the form of jet flow. Nanoparticle jet flow of MQL grinding is an innovative grinding technology involving special equipment that integrates all advantages of MQL technology and presents better cooling effect and tribological features (Mao et al., 2013). This technology can effectively address the issue of grinding burn and improve the completeness of the workpiece surface (Li et al., 2011b). This technology can also help realise efficient, environmentally friendly, resource-saving, and low-carbon green production with low consumption.

<table>
<thead>
<tr>
<th>Matters</th>
<th>Copper</th>
<th>Aluminium</th>
<th>Copper oxide</th>
<th>Aluminium oxide</th>
<th>Zinc oxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity (W·m⁻¹·K⁻¹)</td>
<td>401</td>
<td>237</td>
<td>19.6</td>
<td>40</td>
<td>100</td>
</tr>
<tr>
<td>Thermal conductivity (W·m⁻¹·K⁻¹)</td>
<td>3000</td>
<td>2300</td>
<td>148</td>
<td>0.613</td>
<td>0.145</td>
</tr>
</tbody>
</table>
The removed volume of unit materials during grinding in the interface of the grinding wheel/workpiece generates a mass of energies. The introduction of MQL with insufficient cooling effect into grinding is more challenging than other cutting methods. So far, only a few research groups have conducted exploratory studies on MQL grinding technology. Baheti et al. (1998) explored the application prospect of MQL in grinding from the aspect of environmental protection and ecology. Their research demonstrates that compared with traditional flood cooling grinding, the costs of MQL grinding fluid are lower by 65%, and device investment is also lower by 22%. In addition, using naturally degraded synthetic esters as lubricants, the grinding fluid has minimal harmful effects on the environment and human (Li et al., 2012a). da Silva et al. (2007) studied the surface completeness of the workpiece, specific energy, and abrasion contrast of a grinding wheel under different conditions, including dry grinding, flood cooling wet grinding, and MQL. Their results show that compared with the other two flood cooling methodology conditions, MQL provides effective lubrication but insufficient cooling effect. The completeness of the processed workpiece surface also deteriorates. Tawakoli et al. (2009) researched the impact of grinding parameters on the workpiece surface quality in a flat grinder experiment. Compared with flood cooling wet grinding, the workpiece surface quality improves under the conditions of optimisation of grinding consumption and feed liquid parameters, with improved quality, reduced tangential grinding force, and decreased specific grinding energy. Barczak et al. (2010) performed a precision surface grinder experiment to study the grinding power, grinding force, grinding temperature and surface roughness contrast of MQL grinding and flood cooling dry grinding. Their results show that using a suitable material removal rate improves the grinding force and grinding power of MQL compared with that of flood cooling methodology. Nevertheless, the roughness of the workpiece surface and residual stress are inferior to those of flood cooling methodology. Prof. Wang Ailing (Wang et al., 2005) conducted a minimum cutting-in (5 μm) grinding contrast experiment on a precise DC grinder with the water droplet processing liquid attached by minimum quantity oil film, emulsion solution, soluble concentrates, minimum quantity spray, and minimum quantity oil mist processing liquid. Furthermore, they measured the grinding force, surface roughness, temperature of the grinding zone, and grinding ratio. Results show that the cooling effect of the water droplet processing liquid attached by minimum quantity oil film is inferior to traditional processing liquid such as emulsion solution and soluble concentrates, yet presenting sound lubricating property. Excellent advantages are also presented in terms of processing precision and grinding wheel life. However, this method can be applied to grinding only under low grinding heat conditions because of the limited heat transfer of a minimum quantity of water drops.

The extensive use of grinding fluid in flood cooling methodology damages the environment and harms human health, and the cooling effects of MQL grinding are severely insufficient (Li et al., 2008; Weinert et al., 2004; Sadeghi et al., 2009). Accordingly, nanoscale solid particles were injected into the grinding zone in the form of a jet flow after the mixing and atomisation of nanoparticles, lubricants (oil or oil-water mixture), and high-pressure gas because of the prior heat transfer of solid particles compared with liquid and gas. In this way, the defects of MQL cooling effect can be offset, which can greatly improve the production environment, save energy, reduce costs, and enable low-carbon manufacturing. Furthermore, lubricants are more effectively injected into the grinding zone by breaking the airbond, thereby improving the effective flow rate of the grinding wheel/workpiece interface grinding medium. The fluid dynamic
pressure and introduction force generated by the grinding medium in the wedge-shaped contact area, as well as the deflection deformation of the principal axis of the grinding wheel, decrease compared with wet grinding. The precision of the workpiece processing is also improved. Furthermore, given the special lubricating property and tribological properties of nanoscale solid particles for jet flow, a nanoparticle shearing oil layer can be found on the interface of the grinding wheel/workpiece (Kalita et al., 2012b). This layer can enhance the lubricating property of MQL grinding, which has practical implications. In the present research, modelling and numerical simulation of a nanoparticle jet flow of MQL grinding temperature field were conducted.

The development of industrial technologies has led to the extensive use of ceramic materials with high strength, high hardness, high chemical stability, low thermal expansion coefficient, and abrasion resistance in the fields of machinery, metallurgy, chemical industry, energy, and bio-engineering (Li et al., 2011c). The reason is the special physical and chemical properties of these ceramic materials that make them difficult to process. The processing equipment and tools must have higher hardness to enable ceramic material processing (Li et al., 2012b; Hou et al., 2011).

Given the hardness and brittleness of engineering ceramics and their completely different nature compared with metal materials, using conventional cutting methods for metal processing is difficult (Hou et al., 2012). Most ceramic materials are poor conductors of electricity, and their electrical processing methods such as electrical discharge machining (EDM) are generally not applicable (Li et al., 2012c). Consequently, the processing of ceramic materials is greatly limited, and ceramic materials cannot be widely used. Methods of ceramic material processing are mainly classified as machining, EDM, combined machining, chemical processing, high-energy beam processing, and secondary energy method. Machining includes rubbing, polishing, grinding, honing, etc., whereas non-traditional processing includes laser machining, EDM, ultrasonic machining, water-jet cutting, heat-assisted processing, etc.

In ceramic materials processing, the grinding power is relatively large, i.e., a high energy is needed to remove material per unit volume. Most of this energy is transferred to the workpieces, and only a small amount is transferred to the surrounding medium. Considering the low thermal conductivity of the ceramic materials, the energy is difficult to transfer deep into the workpiece. This phenomenon results in energy aggregation on the workpiece surface, with a high local temperature formed on the surface. An excessive temperature of ceramic materials may cause burns and residual tensile stress on the workpiece surface (Hou et al., 2010). Therefore, the fatigue strength, dimensionality, and shape accuracy of the workpieces must not be ignored.

Zirconia ceramic materials are considered as ideal medical restoration materials because of their excellent biocompatibility, corrosion resistance, abrasion resistance, and aesthetic properties. These materials are widely used in mouth rehabilitation and biological-joint manufacturing. However, the inherent brittleness limits their clinical application. With the development of technologies such as nanotechnology, nanoceramics are considered as the most effective way to resolve the brittleness of ceramics.

Compared with ordinary ceramics, the fracture toughness of nanoceramics has been greatly improved, thereby guaranteeing a removal mechanism of material microstructure plasticity. Thus far, reports on the grinding of nanoceramics are limited, and further studies are required on the processing mechanism and surface integrity (Gu et al., 2004). In this study, ANSYS finite element analysis software was used to simulate and analyse
the grinding temperature of nanozirconia ceramics. The temperature fields under different grinding conditions were also compared. The effects of grinding parameters on grinding temperature were discussed as well.

2 Mathematical model of the temperature field

With the planar shallow-cut grinding as the study objective, Figure 1 shows heat source conduction of the grinding zone. We assumed that the grinding contact arc-zone AA′B′B is the band-shape heat source, the Y-direction is infinitely long, the intensity of the heat source is \( q_m \) [J/(m²·K·s)], the contact arc length is \( l_c \), and the heat source AA′B′B is the set of countless linear heat sources \( d_{xi} \). One linear heat source \( d_{xi} \) was taken with the intensity of \( q_md_{xi} \), which moved along the X-direction with velocity \( V \).

**Figure 1** Planar heat source conduction

The temperature-rise equation of point \( m(x, 0, z) \) from linear heat source \( q_md_{xi} \) with width \( dx \) is:

\[
d\theta_m = \frac{q_m}{\pi\lambda} \exp\left[\frac{(x-x_i)\nu_m}{2\alpha}\right] k_0 \frac{\nu_m}{2\alpha} \sqrt{\frac{(x-x_i)^2 + z^2}{2\alpha}} dx_i
\]

(1)

The temperature variation equation of point \( m \) from the entire heat source belt is:

\[
\theta_{(x,z)} = \frac{q_m}{2\pi\lambda} \int_{-l}^{l} dx_i \int_0^t \frac{dt}{t} \exp\left[-\frac{(x-x_i+\nu_mt)^2 + z^2}{4\alpha t}\right]
\]

\[
= \frac{q_m}{2\pi\lambda} \int_{-l}^{l} e^{-\frac{(x-x_i)^2}{2\alpha}} K_0 \frac{\nu_m}{2\alpha} \sqrt{\frac{(x_i-x)^2 + z^2}{2\alpha}} dx_i
\]

(2)

Where order
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\[ u = \frac{(x-x')v_w}{2\alpha}, \quad X = \frac{v_w x}{2\alpha}, \quad Z = \frac{v_w x'}{2\alpha}, \quad L = \frac{v_w}{2\alpha} \]  

(3)

By substituting equation (3) into equation (2), we get the following equation:

\[ \theta_{1,1,z} = \frac{2q_m\alpha}{\pi \lambda v_w} \int_{X-L}^{X+L} e^{-\alpha \sqrt{u^2 + Z^2}} du \]  

(4)

where \( q_m \) is the surface heating source intensity of a semi-infinite body, \( \lambda \) as the thermal conductivity of the workpiece material \([W/(m\cdot K)]\), \( \alpha \) as thermal diffusivity \([cm^2/s]\); \( \alpha = \lambda / \rho c_p \), \( c_p \) is the specific heat capacity \([J/(kg\cdot K)]\), \( \rho \) is the density \([g/cm^3]\), \( v_w \) is the movement velocity of the heat source, \( K_0(u) \) is the zero-order modified Bessel function of the second kind, and \( l \) is surface heating source width.

2.1 Energy proportionality coefficient

We assume that the theoretical contact area and actual contact area of the grinding wheel and workpiece is \( S \) and \( S_e \) respectively, and \( q_w \) is the internal input energy in unit time. Thus, we obtain:

\[ q_w = \frac{1}{2} (\theta_{e,b}) \left[ 2(\lambda c_p) v_w S_e l \right]^{\frac{1}{2}} \]  

(5)

The input energy of the grinding wheel in unit time is:

\[ q_s = \frac{1}{2} (\theta_{e,b}) \left[ 2(\lambda c_p) v_s S_e l \right]^{\frac{1}{2}} \]  

(6)

The output energy of nanofluids in unit time is:

\[ q_f = \frac{1}{2} (\theta_{e,b}) \left[ 2(\lambda c_p) v_f l \right]^{\frac{1}{2}} \]  

(7)

The proportionality coefficient \( R_w \) of the input energy is:

\[ R_w = \frac{q_w}{q_s + q_f} = \frac{1}{1 + \left[ (\lambda c_p) v_s S e \right] S v_w + \left[ (\lambda c_p) v_f l \right] v_s} \]  

(8)

where \( v_s \) is the peripheral speed of the grinding wheel, \( b \) is the grinding width, \( (\lambda c_p) \) is the performance parameters of the workpiece, \( (\lambda c_p) \) is the performance parameters of the grinding wheel and \( (\lambda c_p) \) is the performance parameters of the nanofluids.

The surface heating source intensity of the workpiece is:

\[ q_m = R_w F v_s / b \]  

(9)
3 Numerical simulation of temperature field

3.1 Simulation conditions

The planar grinding process was regarded as the movement of planar heat source on the workpiece surface, and the temperature field rules of nano-ZrO$_2$ dental ceramic at 25°C were studied. The material properties and grinding parameters are shown in Tables 1 to 3.

Table 1 Performance parameters of Nano-ZrO$_2$ dental ceramic

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m$^3$)</td>
<td>5,500</td>
</tr>
<tr>
<td>Coefficient of thermal conductivity</td>
<td>3.5</td>
</tr>
<tr>
<td>Specific heat (J/kg·K)</td>
<td>660</td>
</tr>
<tr>
<td>Coefficient of thermal expansion ($10^{-5}$/K)</td>
<td>9.6</td>
</tr>
<tr>
<td>Modulus of elasticity (GPa)</td>
<td>209</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Breaking tenacity (Mpa)</td>
<td>8.1</td>
</tr>
</tbody>
</table>

Table 2 Technological parameters of grinding

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed of grinding wheel ($v_w$)</td>
<td>30 m/s</td>
</tr>
<tr>
<td>Work speed ($v_o$)</td>
<td>3 m/min</td>
</tr>
<tr>
<td>Grinding depth ($a_o$)</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Grinding width ($b$)</td>
<td>4 mm</td>
</tr>
<tr>
<td>Speed of grinding wheel ($v_w$)</td>
<td>40 m/s</td>
</tr>
<tr>
<td>Work speed ($v_o$)</td>
<td>6 m/min</td>
</tr>
<tr>
<td>Grinding depth ($a_o$)</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>Speed of grinding wheel ($v_w$)</td>
<td>50 m/s</td>
</tr>
<tr>
<td>Work speed ($v_o$)</td>
<td>10 m/min</td>
</tr>
<tr>
<td>Speed of grinding wheel ($v_w$)</td>
<td>60 m/s</td>
</tr>
<tr>
<td>Work speed ($v_o$)</td>
<td>3 m/min</td>
</tr>
</tbody>
</table>

Table 3 Performance parameters of cooling and lubrication approaches

<table>
<thead>
<tr>
<th>Cooling and lubrication approaches</th>
<th>Performance parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood cooling methodology</td>
<td>Water-based grinding fluid; delivery value, 100 l/min</td>
</tr>
<tr>
<td>MQL</td>
<td>Purely oil-based (35 ml/h)</td>
</tr>
<tr>
<td>Nanoparticle jet flow of MQL</td>
<td>Carbon nanotube particles with a diameter of 10–20 nm; oil-based (vegetable oil); volume fraction, 1%; delivery value, 35 ml/min</td>
</tr>
<tr>
<td>Dry grinding</td>
<td>None</td>
</tr>
</tbody>
</table>

3.2 Finite element grid division

In the finite element analogue simulation, grid division has a decisive effect on the calculation precision. A lower width of the grid division leads to higher corresponding computational accuracy and greater computation time needed. Hence, to improve computational accuracy and efficiency in this model, the DC3D8 mode of an eight-node implicit linear heat-conduction unit was adopted for grid division of the workpiece.

3.3 Thermal loading

The mobile heat source model was discretised, i.e., in the time of one analysis step, and a uniform and constant heat source was loaded onto a certain area. In the next analysis step, the heat source was moved to another area. The previous analysis results were used as the
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initial conditions in the simulation to achieve continuous moving loading of the heat source.

4 Result analysis

4.1 Temperature distribution along the grinding direction

In planar grinding, the workpiece surface is influenced by the heat source effects with the constant feeding of the grinding wheel, and the heat flux density and temperature field change with time. The rules of temperature variation at different positions are shown in Figure 2.

**Figure 2** Temperature distribution at different points along the grinding direction (see online version for colours)

Figure 2 shows that along the feeding direction of the grinding wheel, seven time nodes (t from 0.01 s to 0.07 s) on the finished surface were successively taken with equidistance to acquire a temperature-time diagram. The temperature variations of the six nodes were almost identical, i.e., progressing forward in the form of waves. When the heat source moved to the grinding arc-zone of nodes, the node temperature rapidly increased and reached the peak value when the heat source was about to leave the grinding arc-zone. When the position of heat source was removed from the grinding arc-zone, the energies of each node rapidly diffused with the temperature gradually stabilising. Furthermore, the nodes closer to the heat source had higher equilibrium temperature at the steady state.

4.2 Temperature distribution along the workpiece thickness direction

Figure 3 shows the surface temperature field variation rules along the workpiece thickness direction of nano-ZrO$_2$ dental ceramic under the condition of nanoparticle jet
flow of the MQL. During grinding, the heat source had an extremely short effect time on the workpiece surface. In addition, the relatively small thermal conductivity of the workpiece material hindered the timely diffusion of the input heat on the workpiece surface from the heat source, thereby forming a local high temperature. The workpiece surface temperature was also much higher than the subsurface temperature of the workpiece, presenting a relatively large temperature gradient along the direction of workpiece thickness. The temperature variation of the workpiece along the thickness direction was mainly related to the material properties of the heat source and workpiece. The coefficient of thermal conductivity of the workpiece significantly affected the longitudinal temperature variation.

**Figure 3**  Temperature distribution diagram of nodes along the direction of grinding depth (see online version for colours)

As shown in Figure 3, three points 0, 0.5, and 1.5 mm from the workpiece’s finished surface along the workpiece thickness were taken to generate a time-temperature diagram. The node at \( Z = 0 \) mm located on the surface of the grinding zone and its maximum temperature (i.e., the maximum temperature in the grinding zone) was about 640°C. The node at \( Z = 0.5 \) mm had a maximum temperature that dropped to about 420°C. The node at \( Z = 1.5 \) mm had a temperature curve that almost overlapped, and the maximum temperature at the steady state was about 290°C. The temperature curve of each node showed that in planar grinding, the node farther from the grinding surface was less affected by the mobile heat source based on the temperature variation below the grinding surface. At \( Z < -1.5 \) mm, the temperature of nodes varies along the direction of grinding depth.
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4.3 Influence of wheel peripheral speed on the grinding temperature field

For the zirconia ceramics, simulation of the grinding temperature field was conducted with different wheel peripheral speeds of 30, 40, 50, and 60 m/s, workpiece speed of 6 m/min, and grinding depth of 0.5 mm. Figure 4 shows the workpiece temperature rules on the four wheel peripheral speed along with time. The influences of wheel peripheral speed on the grinding temperature field were similar, and the temperature gradient along with time was large. This finding was due to the fact that the number of grinding grains that participated during grinding within the same period relatively increased in the process of grinding with increased wheel peripheral speed. Consequently, the effective tangential grinding force decreased and the energy distribution coefficient transported into the workpiece increased. With increased wheel peripheral speed, the energy of the grinding grain taken from the grinding zone decreased, leading to a large amount of heat remaining in the workpiece. Moreover, the low heat-transfer coefficient of the ceramic material resulted in the accumulation of a large amount of heat energy on the surface, and a large temperature gradient appeared in the temperature distribution layer.

Figure 4 Relationship of wheel peripheral speed with temperature field (see online version for colours)

4.4 Influence of workpiece speed on the grinding temperature field

For the zirconia ceramics, simulation of the grinding temperature field was conducted with workpiece speeds of 3, 6, and 10 m/min, wheel peripheral speed of 60 m/s, and grinding depth of 0.5 mm. The workpiece temperature rules on the three workpiece speed along with time are shown in Figure 5.
With increased workpiece feed speed, the grinding temperature on the finished surface decreased mainly because the specific grinding energy was on a declining curve. However, the grinding energy increased in the grinding process with increased workpiece feed speed. Consequently, the grinding temperature decreased with increased workpiece speed. Given the small thermal conductivity of the nanozirconia workpiece materials, the input heat on the workpiece was concentrated in the surface layer, making the decline of specific grinding energy decrease the impact on the surface grinding temperature. With increased workpiece feed speed, although the grinding temperature gradually decreased, the grinding temperature along with time and the grinding temperature curve showed no significant changes.

4.5 Simulation analysis under different cooling and lubrication conditions

Figure 6 shows the simulation results of the temperature field of nano-ZrO₂ dental ceramics in four cooling and lubrication approaches. The regularities of temperature field distribution were the same. However, the different thermal ratios through grinding media led to variations in the temperatures of the grinding zone. Based on the excellent heat-transfer property of nanofluids, the temperature of the grinding zone was greatly reduced. As shown in Figure 7, the location with the maximum temperature difference was in the grinding zone, indicating that only with the injection of lubricants into the grinding zone can the maximum grinding temperature be reduced to the maximum extent so as to prevent grinding burns and other issues during grinding. Under the four cooling and lubrication conditions, the variations in grinding temperature along the grinding width were insignificant, but the temperature variations were significant. The addition of
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nanoparticle MQL to grinding remarkably weakened the temperature effect of the grinding zone.

**Figure 6** Temperature distribution along the grinding direction (see online version for colours)

![Figure 6](image)

**Figure 7** Regularities of temperature distribution along the direction of grinding width (see online version for colours)

![Figure 7](image)

Figure 8 shows the regularities of distribution of grinding temperature along the direction of workpiece thickness under the four grinding conditions. A large temperature gradient can be observed. The temperature gradient of dry grinding obviously exceeded that of MQL. In addition, in the deep layer at $Z = 2.8$ mm, the internal grinding temperature was close to the initial temperature.
5 Conclusions

The heat-transfer model of the surface grinding temperature field with the nanoparticle jet flow of MQL, as well as the proportionality coefficient model of an energy input workpiece, was established. Numerical simulation of the surface grinding temperature field of nano-ZrO$_2$ dental ceramics was performed. In the grinding, the surface temperature of the workpiece was the highest, with a large temperature gradient along the direction of workpiece thickness. Furthermore, the grinding depth greatly affected the grinding temperature. With increased cut depth, the peak value of grinding temperature was rapidly elevated. Increased workpiece feed speed led to decreased grinding temperature on the finished surface. The increased wheel peripheral speed caused by the low heat-transfer coefficient of the ceramic material resulted in the accumulation of a large amount of heat energy on the surface, and a large temperature gradient appeared in the temperature distribution layer.

The distribution rules of the temperature field of nano-ZrO$_2$ dental ceramics was the same in four cooling and lubrication approaches, namely, dry grinding, flood cooling methodology, MQL, and nanoparticle jet flow of MQL. Given the different thermal ratios from the grinding medium, the temperature of the grinding zone varied. Meanwhile, the outstanding heat-transfer property of nanofluids greatly reduced the temperature in the grinding zone. Under four cooling and lubrication conditions, the grinding temperature only slightly changed along the direction of grinding width, but with significant temperature variation. MQL with nanoparticles most significantly affected the reduction of the temperature effect of the grinding zone. During grinding, only with the effective injection of grinding fluid into the grinding zone can the temperature of the grinding zone be reduced to the maximum extent so as to prevent grinding burns and improve workpiece surface completeness.
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References


