The influence of wear volume on surface quality in grinding process based on wear prediction model

Wei Cao1 · Zhao Han1 · Ziqi Chen1 · Zili Jin1 · Jiajun Wu1 · Jinxiu Qu1 · Dong Wang2

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Abstract
During the grinding process, the workpiece is not only cut by abrasive grains but adhesive wear also occurs due to high temperature and heavy load, reducing the surface quality of the workpiece. In this paper, a wear test method considering speed, force, wear coefficient, temperature and hardness was proposed. A new physical model of wear prediction was established based on the finite element method and numerical simulation technology. The wear test was carried out on a grinding machine. Comprehensive research on the relationship between the force, temperature, surface morphology and wear volume of the grinding process was studied. The relationship between workpiece speed, grinding depth, cooling lubrication conditions and wear volume of the grinding process was studied. The results show that the wear model can achieve numerical prediction and trend prediction of grinding temperature, surface profile and wear volume, with relative errors between the theoretical and actual values of wear and grinding temperature of 9.84% and 2.07%, respectively. This study provides support for wear prediction and surface quality control of the grinding process from the perspective of temperature and micro material removal.

Keywords Grinding · Surface quality · Wear model · Wear volume · Grinding temperature · Surface morphology

1 Introduction

With the rapid development of industrialisation, grinding is used widely in aviation manufacturing and other fields, but the high temperature, speed and heavy load of the working conditions cause severe wear on the surface of the workpiece and reduce the surface quality. Research on wear prediction models and wear mechanisms can predict the wear volume and trend to provide support for controlling the surface quality of workpieces and to reduce the expense of grinding quality tests. Therefore, this research has great significance. However, the factors affecting wear volume vary, including temperature, speed, force, wear coefficient and hardness. For this reason, scholars have performed much research on wear volume.

Naskar et al. [1] studied the wear mechanism of an electroplated CBN grinding wheel under different conditions of grinding fluid cooling and lubrication, and its influence on grinding performance, which contributed to the improvement of grinding wheel dressing and grinding quality. Kahraman and Ozturk [2] designed a grinding wheel with a C-shaped groove and used it in the test. According to the test data, the linear regression equation that can predict the roughness was obtained, and combined with Monte Carlo simulation technology, the measurement uncertainty of surface roughness was predicted. This method can predict in advance the surface roughness of the grinding wheel under various grinding conditions. Aydin et al. [3] studied the wear performance of a diamond saw blade cutting rock, developed a saw blade wear measurement method based on the optical imaging principle.
and used this method to compare the influence and contribution of various processing parameters and the specific wear rate (SWR), which suggested the accuracy of the SWR prediction model. Yu et al. [4] proposed a novel phenomenological model for progressive wheel wear to study the failure behaviour of grinding wheels at high temperatures. The results show that a high-efficiency deep grinding (HEDG) configuration can remove a greater amount of material for the same amount of wheel wear. Dai et al. [5] categorised abrasive wear into four types, crescent depression on the rake face, abrasion on the flank face, grain microfracture and grain macrofracture, and discussed the influence of abrasive wear on material removal behaviour. The results show that the material removal efficiency is proportional to the wear width on the grain rake face. Li et al. [6] studied the evolution of concave wear behaviour and its effect on material removal at different thicknesses of un-deformed chips and grinding wheel speeds, which provided technical support for monitoring grain wear during grinding. Jiang et al. [7] established a ground surface topography model based on the microscopic interaction mechanism model between grains and the workpiece in the grinding contact zone. They simulated the grinding surface profile but lacked research on the mechanism of grinding and the influence of machining parameters on the surface quality. Oo et al. [8] proposed a tool wear monitoring method based on image processing and established the correlation between grinding belt wear and abrasive grain area features. However, wear behaviour has not been studied from the perspective of the grinding mechanism.

To date, scholars have performed much research on wear evolution in the grinding process, but most of the research is oriented toward the surface failure mechanism of grinding wheels. Although a few scholars have studied the material removal behaviour caused by single grinding wheel abrasive grain wear, they have not studied the material removal mechanism from the perspective of material wear.

Sieniawski and Nadolmy [9] studied the effect of different machining parameters on the grinding force of CrV12 steel. Li et al. [10] established a grinding temperature model for a free-form surface workpiece and verified the model by testing. However, he used a thermocouple to collect temperature data, which requires the workpiece to be cut into two parts, and this has an impact on the test results. Curtis et al. [11] analysed the temperature field, residual stress and morphology in the grinding process but did not study the interaction mechanism between them. Li et al. [12] established a material removal model for double-sided grinding, which can predict the grinding profile of the workpiece surface. They analysed the material removal uniformity according to the results calculated by the model but obviously did not consider the influence of temperature on the material removal mechanism. Qu et al. [13] established a new workpiece surface roughness prediction model according to Young’s modulus formula, improved the grinding thickness index according to the energy balance assumption and reduced the prediction deviation from 63.9 to 13.9%, but a large part of the grinding energy was converted into heat energy, which should also be considered. Xi et al. [14] studied the grinding performance of Ti3AlNb intermetalics using GC and PA wheels and compared the efficiency and processing quality between the two grinding wheels, which provided support for the selection of grinding wheel materials in grinding applications. Miao et al. [15] compared the grinding force and surface quality under different grinding conditions and provided the optimal machining parameters, but the optimal machining parameters should be determined by considering many factors, such as temperature, surface topography, surface roughness and wear amount.

The above research provided the basis for grinding from the temperature, force and material removal mechanism, but there is no research on the relationship between temperature, force, surface morphology, surface roughness and wear.

Hsu et al. [16] estimated statistics on many factors that affect the wear amount, such as force, temperature, speed, lubrication conditions and cooling conditions. Zhang et al. [17] studied the relationship between friction dissipation power and wear rate but did not consider the change in lubrication conditions. Ma et al. [18] proposed an elastohydrodynamic lubrication model, and the wear amount was studied from the three aspects of temperature, pressure and speed by the integrative test bench of an axis piston pump. However, he did not study the response of different lubricating media to wear. Ramalho [19] used the Archard wear model to study the relationship between contact pressure, speed and wheel-rail wear. However, to date, the maximum running speed of the train has reached more than 600 km/h, and the contact temperature between the wheel and rail is also affected by the speed; therefore, if this model can be linked with temperature and improved, it can provide more support for train maintenance.

The above scholars have studied the relationship between various factors and wear amount; however, if a wear prediction model considering all the above factors can be established, the prediction accuracy would be substantially improved.

Previous research has achieved satisfactory results, and their respective research contents are summarised in Fig. 1, but there are still some defects and knowledge gaps. (I) The proposed wear model and wear mechanism are not suitable for grinding processes. (II) Lack of a wear prediction model considering all the above factors can be established, the prediction accuracy would be substantially improved. (III) There is no comprehensive research on the relationship between temperature, force, surface morphology and grinding process wear.
In this paper, a wear test method of the grinding process was proposed, which can change the workpiece speed, grinding depth and cooling lubrication conditions at the same time, while considering the effects of speed, contact force, temperature, wear coefficient and hardness on the wear volume. A new prediction model of wear and surface topography of the grinding process was established by using the finite element method and numerical simulation technology. The influence of different processing parameters on the wear volume was analysed and the wear mechanism of the grinding process based on the temperature field, wear volume and surface morphology was studied, providing support for controlling the surface quality of the workpiece.

2 Wear failure mode of the grinding process

Grinding is widely used in ultra-precision machining of thin-wall parts; the small cutting feeds of abrasive grains on the surface of the grinding wheel (abrasive wear) result in higher machining accuracy than cutting. However, the working conditions of high temperature, high speed and heavy load cause adhesive wear of the surface material, which would affect the surface quality of grinding.

Gao and Wang et al. [20, 21] divided the grinding process into two periods: primary grinding and secondary grinding, as shown in Fig. 2. The primary grinding is abrasive wear solely caused by the abrasive cutting
material, and the volume of material removal caused by it is determined by the cutting depth of the layer of abrasive, which is defined as macro material removal. The secondary grinding is adhesive wear caused by high temperature and pressure at the bottom of the contact area between the abrasive and workpiece, which is defined as micro material removal. Therefore, the total volume of material removal is the sum of the two stages.

Although the material removal volume of secondary grinding is small, it plays a decisive role in grinding surface quality. Therefore, this paper focuses on the material removal mechanism, wear volume and surface quality control of secondary grinding.

The grinding machine can control the processing parameters, including workpiece speed, grinding depth and cooling lubrication conditions. These parameters affect the relative speed, temperature, grinding force, wear coefficient and material properties, so the wear process of a given grinding machine is complex. Due to the different diameters of the abrasive grains on the surface of the grinding wheel, the contact force of each single abrasive grain in the contact area is also different, which leads to a change in the contact pressure and wear depth per unit area. Therefore, in this paper, the contact area between the grinding wheel and the workpiece was discretised to study the wear volume caused by a single abrasive grain. This procedure can not only calculate the overall wear volume but also allows study of the wear mechanism.

3 Establishment and calculation of the wear prediction model

3.1 Basic calculation model of wear volume

In 1953, J.F. Archard of the United States put forward the Archard adhesive wear theory, which holds that when the surfaces of the friction pair are in relative sliding motion, the adhesive point shears and breaks due to the adhesive effect, resulting in a large micro volume falling off the material [22]. Based on the Archard wear model, the wear model of the grinding process was established

\[
\frac{dh}{ds} = \frac{K}{H} \rho
\]  

(2)

The integral form of Eq. (2) is

\[
h = \int_0^s \frac{K}{H} \rho ds = \int_0^s kpd\]

(3)

where \(h\) is the wear depth, \(\rho\) is the contact pressure and \(k\) is the wear coefficient.

3.2 Contact pressure

It is assumed that the abrasive grains are spherical. Hou and Komanduri [23] estimated statistics on the diameter of the abrasive grains of the grinding wheel. The results show that the diameter of abrasive grains obeys a normal distribution, and the probability function is

\[
P(D_{gx}) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{D_{gx} - D_{mean}}{\sigma}\right)^2\right]
\]

(4)

where \(D_{gx}\) is the abrasive diameter, \(D_{mean}\) is the average diameter of abrasive grains and \(\sigma\) is the standard deviation.

In this paper, a grinding wheel with a granularity of 46 was selected for testing, and the grain diameter ranged from 38 to 45 μm, which would affect the normal contact force. When the direction of motion of a single abrasive grain is horizontal relative to the surface of the workpiece, it is said to be in the ploughing stage, which also indicates that the grinding depth is at its maximum, as shown in Fig. 3. Because the abrasive grains in the ploughing stage are very similar to the Brinell hardness test indicator, and the white corundum abrasive grains can be regarded as rigid bodies by their characteristic of high hardness, the contact force can be deduced according to the principle of Brinell hardness measurement [24].

\[
H = \frac{2F_b}{\pi D_{gx} \left(\frac{D_{gx}}{2} - \sqrt{\frac{D_{gx}^2}{4} - d^2}\right)}
\]

(5)

The normal grinding force \(F_n\) can be obtained by cutting angle \(\alpha\)

\[
\alpha = \arccos \left(1 - \frac{2a_c}{D_{gx}}\right)
\]

(6)

\[
F_n = F_b (\cos \alpha - \mu \sin \alpha)
\]

(7)

where \(F_b\) is Brinell hardness test force, \(d\) is indentation diameter, \(\mu\) is the friction coefficient and \(a_c\) is grinding depth.
As shown in Fig. 3, when the cutting angle of the abrasive grains is constant, the contact area between the abrasive and the workpiece is also constant (represented as the red area in Fig. 3), and its longitudinal projection area is $S_p$. In this paper, the model of a single abrasive grain was established involving the contact pressure per unit area, the abrasive diameter was normally distributed and the contact pressure $p$ between the grinding wheel and the workpiece was discretised.

$$S_p = \frac{1}{2} \pi \left[ \frac{(D_{gx})^2}{2} - \left( D_{gx} - a_x \right)^2 \right]$$  \hspace{1cm} (8)

$$p = \frac{F_n}{S_p}$$  \hspace{1cm} (9)

### 3.3 Grinding temperature

Some scholars assumed that the wear coefficient $k$ is not affected by temperature. This assumption is feasible at low temperatures, but severe wear is always accompanied by high temperatures such as in grinding, during which the temperature may exceed 700 °C and introduce error in wear prediction. Therefore, the calculation of the temperature field is necessary.

The work done by the grinding wheel in grinding the workpiece is converted into heat flow [25], and the grinding process is performed by all the single abrasive grains; therefore, the premise of calculating the force is to obtain the number of abrasive grains. In this work, a new heat model was established based on the granularity (grain size) and structure number $Q$ (abrasive ratio) of the grinding wheel.

$$q_t = \frac{\mu F_n N (v_s + v_w) \times 10^{12}}{l_g b}$$  \hspace{1cm} (10)

where $q_t$ is the heat flux in contact area, $v_s$ is the speed of grinding wheel, $v_w$ is the speed of workpiece, $l_g$ is the contact arc length and $b$ is the contact width.

It is assumed that the abrasive grains are evenly distributed on the surface of the grinding wheel, as shown in Fig. 4. Then, the average clearance of abrasive grains $\Delta$ can be calculated by the abrasive ratio $V_g$ (proportion of abrasive volume to total volume) of the grinding wheel, and the number of abrasive grains $N$ in the contact area can be obtained.

$$V_g = \frac{62 - 2Q}{100}$$  \hspace{1cm} (11)
In addition, the grinding fluid flows into the clearance between the abrasive grains and the grinding area to produce a rapid convective heat transfer effect [26]. Therefore, in this paper the abrasive grains on the grinding wheel surface and the grinding fluid are regarded as a mixture and the composite thermal conductivity and volumetric specific heat can be written as:

\[ \lambda = V_g \times \lambda_g + (1 - V_g) \times \lambda_l \]  

(14)

\[ (\rho c)_s = V_g \times (\rho c)_g + (1 - V_g) \times (\rho c)_l \]  

(15)

where \( \lambda \) is the coefficient of thermal conductivity, \( \rho \) is the density, \( c \) is the specific heat capacity and the subscripts \( g \) and \( l \) represent grinding wheel abrasive particles and grinding fluid, respectively.

The heat flux generated by grinding would be transmitted to the workpiece and grinding wheel in a certain proportion [27], which is determined by the material properties.

The finite element method can be used to solve for heat conduction. First, the model is established, and the material properties are imported. Then, the contact area mesh is refined, and the mesh type is set to C3D8T, an eight-node thermally coupled hexahedral element. The surface of the workpiece is divided according to the grinding contact arc length. The numerical calculation result of the heat flux density \( q_w \) is imported into the load and the workpiece temperature is set to 25 °C in the predefined field. Since the convective heat transfer caused by the grinding fluid has been considered in the input load, only the convective heat transfer between the workpiece and the air is added, as shown in Fig. 5a. According to the relative speed, the analytical field calculation formula of each analysis step was deduced and established, as shown in Eq. (18). Finally, the model was calculated, and the result is shown in Fig. 5.

It can be seen that the temperature tends to be stable in the

\[ \Delta = \sqrt{\frac{\pi D^3_{mean}}{6V_g}} \]  

(12)

\[ \varepsilon_w = \left[ 1 + \sqrt{\frac{(\lambda c)_g V_g}{(\lambda c)_l V_l}} \right]^{-1} \]  

(16)

\[ q_w = \varepsilon_w q_l \]  

(17)

where \( \varepsilon_w \) is the proportion of heat transferred to the workpiece.

Fig. 5  Modeling and results of grinding temperature
tenth analysis step, and the stable temperature was used as the statistical index.

In this work, GH4169 nickel-based superalloy was used for the grinding test. The GH4169 nickel-based superalloy, white corundum abrasive and grinding fluid are shown in Tables 1 and 2.

\[ C_{input} = \frac{2}{l_y} \sum_{i=1}^{n} \frac{1}{l_x} \]

where \( i \) is the number of analysis steps, and \( X \) is the distance between each point where the load was applied and the end of the workpiece.

3.4 Wear coefficient \( K \), material hardness \( H \) and relative sliding distance \( s \)

Lee and Jou [29] improved the Archard wear model and obtained the relationship between temperature and hardness \( H \). Rabinowicz [30] tested and summarised the wear coefficient \( K \) under different lubrication conditions, as shown in Table 3. The content of aluminum oxide in white corundum abrasive grains is more than 99%, so the contact between white corundum and GH4169 is metal-nonmetal. In addition, oil-based grinding fluid has good lubrication performance, and water-based grinding fluid also contains approximately 50% emulsion. Therefore, according to the table below, the wear coefficients \( K \) of dry grinding, water-based grinding fluid and oil-based grinding fluid are assumed to be \( 1.7 \times 10^{-6} \), \( 1.65 \times 10^{-7} \) and \( 3.3 \times 10^{-7} \), respectively (Fig. 6).

The unit sliding distance \( s \) of the abrasive grain at the contact point can be calculated by integrating the relative sliding speed. Considering the down grinding method (the rotation direction of the grinding wheel is opposite to the direction of movement of the worktable), the sliding distance can be calculated as follows:

\[ s = \int_{t_i}^{t_{i+1}} vdt = \int_{t_i}^{t_{i+1}} (v_x + v_w)dt \]

3.5 Calculation results and discussion

The programme was designed according to the model established in the previous section and is applicable to the wear prediction of any grinding wheel for grinding metal materials. Its flow is shown in Fig. 7:

1) Firstly, input the machining parameters (grinding wheel speed, grinding depth, workpiece speed and cooling and lubrication conditions) and grinding wheel parameters (granularity and abrasive material hardness).
2) According to the input parameters, the geometric characteristics between abrasive grains and materials are obtained, and the contact force and contact pressure are calculated.
3) At the same time, the heat flux distribution ratio and heat flux density of grinding temperature field are obtained according to the input parameters, and the temperature field is obtained by finite element method.
4) The results of contact force model and temperature model are input into Archard wear model, and assuming that the wear depth along the length direction of the workpiece is the same, the surface profile and wear volume of the workpiece can be obtained.

| Table 1 Material properties of GH4169 [28] |
|-------------------------------------------|
| \( \theta/°C \) | 11 | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 1000 |
| \( k/[W/(m \times K)] \) | 13.4 | 14.7 | 15.7 | 17.8 | 18.3 | 19.6 | 21.2 | 22.8 | 30.4 |
| \( c/[J/(kg \times K)] \) | – | – | 481.4 | 493.9 | 514.8 | 539.0 | 573.4 | 707.4 |

| Table 2 Thermal properties of the grinding fluid and white corundum abrasive grains |
|-----------------------------------------------|
| Material science | Water-based grinding fluid | Oil-base grinding fluid | White corundum abrasive |
| Initial viscosity \( \mu_i/(Pa \times s) \) | 0.00415 | 0.0415 | 0.0415 |
| Density \( \rho/(kg/m^3) \) | 1000 | 830 | 3960 |
| Coefficient of thermal conductivity \( k/[W/(m \times K)] \) | 0.68 | 0.15 | 28.82 |
| Specific heat capacity \( c/[J/(kg \times K)] \) | 4180 | 2000 | 765 |

| Table 3 Wear coefficient tested by Rabinowicz [30] |
|-----------------------------------------------|
| Lubrication condition | Metal–metal Similar | Dissimilar Nonmetal–metal |
| Clean surface | \( 1.7 \times 10^{-5} \) | 6.7 \times 10^{-5} | \( 1.7 \times 10^{-6} \) |
| Poor lubrication | \( 6.7 \times 10^{-5} \) | 3.3 \times 10^{-5} | \( 1.7 \times 10^{-6} \) |
| General lubrication | \( 3.3 \times 10^{-6} \) | 3.3 \times 10^{-6} | \( 1.7 \times 10^{-6} \) |
| Good lubrication | \( 3.3 \times 10^{-7} \) | 3.3 \times 10^{-7} | \( 3.3 \times 10^{-7} \) |
The simulation results show that the grinding fluid can reduce the wear, and the smaller the wear volume is, the greater the surface profile fluctuation is (Figs. 8 and 9).

4 Grinding and wear test results and discussion

4.1 Test rig

Twenty-seven workpieces made of GH4169 nickel-based superalloy with a size of 30 mm × 20 mm × 15 mm were tested. An ELB plane grinder was used for datum surface processing. An MYH3070 hydraulic transmission grinder was selected for the test, the spindle speed was 1450 rpm and the grinding wheel speed was 15 m/s. The abrasive grains of the grinding wheel were made of white corundum, the granularity was 181, the structure number was 5 and the diameter was 200 mm. The Testo 868 infrared thermal imager manufactured by Testo was used to collect the thermal images [31]. Its measurement range is −25 ~ 650 °C, its accuracy is ±2 °C and its parameters used in the experiments are described in Table 4. The ZeGage™ plus white light interferometer produced by Zygo was used to measure the surface topography. In this test, three different cooling lubrication conditions were adopted, including dry grinding, water-based grinding fluid and oil-based grinding fluid. Two kinds of grinding fluids are used in the ratio of 5%.

4.2 Test condition

The ELB plane grinder has high machining accuracy. It has a maximum grinding depth of 2 μm, but the abrasive diameter range is 38 ~ 45 μm, which causes a comparison of results under different processing parameters to be ambiguous. Before the test, all workpieces need to have the same precision datum plane. Therefore, in this test, all workpieces were super finished by an ELB plane grinder and then tested by an MYH3070 hydraulic drive grinder, which can not only ensure that the workpieces have the same datum plane but can also produce a clear comparison of results. Before the start of each test, diamond and oilstone were used to correct the grinding wheel to ensure that the working surface of the grinding wheel wore evenly. The grinding wheel speed, grinding depth and grinding fluid were changed during the experiment, aiming the lens of the infrared thermal imager at the grinding contact area, and the data were recorded in real time and then imported into the postprocessing software

Fig. 6 Hardness for GH4169

Fig. 7 Wear prediction steps
for in-depth analysis. After the experiment, the workpieces were placed under a white light interferometer to measure the surface profile and morphology.

The test bench and scheme are as follows. According to the process parameters, a three-factor three-level full factor test was designed.

### 4.3 Testing techniques of grinding temperature and its data processing

Aiming the lens of the infrared thermal imager at the grinding contact area, the data were recorded in real time and then imported into the postprocessing software for in-depth analysis and recording of the hot spot (maximum temperature) \([32]\).

Compared with the FEM results, Fig. 10a shows that there is a heat distribution relationship between the grinding wheel and the workpiece, and the heat flux transferred into the workpiece is greater than that transferred into the grinding wheel. This infrared measurement result is better than that obtained by other scholars using thermocouples. The simulated temperature nephogram is similar to the thermal imaging nephogram; the above results proved that the finite element analysis results are consistent with the measured results (Table 5).
4.4 Testing techniques of surface topography and its data processing

The processed workpieces were placed under the white light interferometer to scan the surface profile. Because the white light interferometer collects the surface profile slowly and has a large number of specimens, a rectangular area of 2.5 mm × 11.65 mm was selected in the middle of the upper surface of the workpieces for sampling. In addition, four contour lines in the width direction of the workpieces were selected in the rectangular area for measurement, and the average value was taken as the final contour line. Figure 10b lists some of the measurement results and sampling methods of the profile. The white light interferometer can measure the surface profile and surface morphology at the same time. The numerical simulation results are similar to the surface profile sampling results, which proves the accuracy of the wear prediction model.

Due to the normal distribution of abrasive size, the contact pressure and wear depth of each contact point are different, resulting in an irregular surface profile of the workpiece after grinding. Therefore, in this paper, the arithmetic mean deviation of the average contour was selected as the baseline height. Then, the unit wear area $S$ was obtained by calculating the area enclosed by the baseline and the contour line below the baseline, which is shown as the blue area in Fig. 10c. The calculation method is shown in Eqs. (18), (19) and (20). Finally, the wear volume $V$ was obtained. A total of 27 groups of data were processed according to the above steps.

$$y = \frac{1}{6000} \sum_{i=1}^{6000} |y_i|$$

$$z = \frac{1}{6000} \sum_{i=1}^{6000} |y_i - y|$$

$$V = S_m \cdot L = L \cdot \int_0^{2500} (z - y_i)dx$$

where $L$ is the measured length of workpiece and $S_m$ is the units wear area.

5 Discussion

By comparing and analysing the wear volume and surface quality and taking the grinding temperature field and surface roughness as evidence, the wear mechanism of the grinding workpiece surface under various machining parameters was studied.

5.1 Relationship between grinding depth and wear volume

The water-based grinding fluid was selected as the cooling and lubricating medium, and the wear volume of each grinding depth under different workpiece speeds is shown in Fig. 11a. The wear volume increases with increasing grinding depth, and the trend of the measurement results is consistent with the simulation results.

After studying the mechanism, it was found that an increase in the longitudinal grinding depth of the grinding wheel would lead to an increase in the cutting depth of a single abrasive grain, and the envelope surface formed by...
Fig. 10  Test results and data processing

(a) Infrared thermography of grinding temperature

(b) Acquisition results of the surface graphology (dry grinding, water-based, oil-based)

(c) Wear profile along the width of workpiece
the workpiece and white corundum abrasive in the ploughing stage would increase. This results in an increase in the contact force of abrasive grains so that the contact pressure per unit area increases and accelerates the wear of the workpiece. In addition, with the increase in abrasive contact pressure, more heat will be generated in the contact area, resulting in an increase in the temperature of the contact pair and a drop in the hardness of the material so that the wear is more severe than before.

From the above analysis, it can be seen that temperature has a crucial influence on the wear volume. Therefore, the temperature field, wear volume, surface morphology and surface roughness of the grinding process were compared and analysed. It is found that the smaller the wear volume is, the smaller the workpiece roughness and the smoother the surface, which is the same as the theoretical simulation results.

When the temperature reaches 240 °C ($a_e = 0.02 \text{ mm}$), the ploughing scratch of a single abrasive grain is very clear, and there is no burn mark. When the temperature reaches 300 °C ($a_e = 0.04 \text{ mm}$), the material near the scratch begins to soften and become fuzzy due to high

| Table 5 Factors and level of the test |
|--------------------------------------|
| Level Factor                        |
|                                      |
| Grinding depth (mm)                  | 1  | 2  | 3  |
| Speed of workpiece (m/s)             | 0.02 | 0.04 | 0.06 |
| Cooling Lubrication Conditions       | Dry grinding | Water-base grinding | Oil-base grinding |
|                                      | Fluid | Fluid | Fluid |

![Fig. 11](image) Comparison of test data under different grinding depths

![Fig. 11](image) Relationship between grinding depth and wear volume

![Fig. 11](image) Comparison of temperature and surface morphology under different grinding depth
temperature, and part of the material is pulled down due to adhesive wear (marked in the red area in Fig. 11b). When the temperature reaches 370 °C ($\alpha_t = 0.06$ mm), the high temperature causes the material to soften severely, the extrusion of the abrasive grains on the material makes these materials stick together and the traction force when the grinding wheel separates from the workpiece causes the material to fall off, forming pits on the surface of the workpiece. In addition, high temperature causes residual stress on the surface of the workpiece, resulting in cracks.

The results show that there is a positive correlation between grinding depth and wear volume. Therefore, under actual working conditions and on the premise of ensuring working efficiency, the longitudinal grinding depth should be reduced to avoid material softening, adhesive wear and cracks caused by high temperature.

5.2 Relationship between workpiece speed and wear volume

The wear volume at each workpiece speed under different cooling lubrication conditions and with a longitudinal grinding depth of the grinding wheel of 0.02 mm is shown in Fig. 12. When the moving speed of the worktable increases from 0.18 to 0.3 m/s, the wear volume increases slowly.

The mechanism was analysed as follows: as the moving speed of the worktable increases, the relative speed of the single abrasive grain and the workpiece increases, the time taken to remove the same volume of material decreases, the heat generated per unit time increases and the hardness of the material decreases.

Because the relative velocity does not change much, the temperature and wear volume change little.

5.3 Relationship between cooling lubrication conditions and wear volume

When the horizontal moving speed of the worktable was maintained at 0.24 m/s, the wear volume under each cooling lubrication condition at different grinding depths is shown in Fig. 13a. The results show that the wear volume is the most severe under dry grinding conditions. The water-based grinding fluid and oil-based grinding fluid can reduce the wear volume by 72.77% and 88.15%, respectively. The relative error of the results is calculated for the above data.

$$\delta_T = \frac{T_m - T_p}{T_p} \delta_V = \frac{V_m - V_p}{V_p}$$

where $T$ represents the temperature, $V$ represents the wear volume, $\delta$ represents the relative error and the subscripts $m$ and $p$ represent the measured value and the theoretical predicted value, respectively.

After calculation, the relative errors between the theoretical and actual values of wear and grinding temperature are 6.14% and 2.07%, respectively. The relative error values are lower than those given by the prediction model given in the study of A. Ramalho and verify the accuracy and effectiveness of the present algorithm.

The reason for this is that in the case of dry grinding, the contact area can only dissipate heat by convection heat transfer with air. In contrast, the convective heat transfer performance of the grinding fluid causes it to take away a
large amount of heat energy, reducing the grinding contact area temperature. With the use of grinding fluid, the material hardness will not drop due to excessive temperature, and wear volume can also be controlled.

In addition, the debris generated by grinding accumulates in the contact area and easily sticks to the workpiece under dry grinding conditions, with a small part of the debris becoming embedded in the abrasive clearance. Grinding fluid can wash away the debris in sufficient time to remove its heat, thereby reducing the wear volume.

Figure 13 shows that the surface quality and roughness worsen with increasing wear volume, and the wear volume is closely related to the grinding temperature. Compared with the dry grinding condition, the water-based grinding fluid and oil-based grinding fluid reduced the temperature by 29.66% and 25.67%, respectively, which indicated that the cooling performance of the water-based grinding fluid was better than that of the oil-based grinding fluid, but the difference was not significant.

Grinding fluid can reduce wear volume by approximately 80%. The anti-wear property of the oil-based grinding fluid is better than that of the water-based grinding fluid because the oil-based grinding fluid easily forms a lubrication film and reduces friction, and the wear coefficient can be reduced several-fold in the contact area between the metal and nonmetal.

In conclusion, the influence of lubrication performance (reduction in wear coefficient) on wear volume is greater than that of cooling performance (reduction in material hardness).
Before actual machining, if the grinding temperature is predicted to be higher than 300 °C, oil-based grinding fluid can be used for cooling and lubrication; otherwise, water-based grinding fluid can be used to focus on cooling, which can improve the surface quality of the workpiece according to the actual situation.

5.4 Study on wear morphology

Figure 14 shows the surface morphology of the workpiece under different cooling lubrication conditions after grinding, with wear volumes of 0.022 mm³, 0.039 mm³ and 0.172 mm³.

As seen from Fig. 14a, there are many scratches (selected area in the white box), which are abrasive wear caused by the single abrasive grain on the workpiece. In addition, due to the adhesive wear between the grinding wheel and the workpiece, some scratches disappear due to the material falling off. However, the oil-based grinding fluid can lubricate the workpiece and cool it more rapidly, which reduces the material removal and makes the surface smoother than before. As shown in the morphology, the wear area and depth are small. The surface is sufficiently smooth and flat to form a mirror effect.

The lubrication performance of water-based grinding fluids is inferior to that of oil-based grinding fluids. As shown in Fig. 14b, there are many black spots on the surface, the colour is darker than that of the oil-based grinding fluid, and the wear range and depth increase. This is because the viscosity of water-based grinding fluid is lower than that of oil-based grinding fluid, thus decreasing its ability to protect the surface of the workpiece.

The morphology of the workpiece under dry grinding conditions is shown in Fig. 14c. The wear depth is increased, the range of the area in which material falls off becomes larger than before and some debris accumulates on the surface without being removed. This is because the high temperature reduces the hardness of the material and causes the material to stick together, finally being removed in block form. In addition, without grinding fluid, the debris on the surface of the workpiece cannot be washed away in a timely manner, so there is still some grinding debris left on the surface.

Therefore, to ensure the grinding surface quality, a smaller cutting depth and workpiece speed should be selected \((a_e = 0.02 \text{ mm}, v_w = 0.18 \text{ m/s})\), and an oil-based grinding fluid should be selected for cooling and lubrication.

6 Conclusion

Based on the finite element method and numerical simulation technology, a physical model of wear prediction of the grinding process was established, and the wear profile, grinding temperature and wear volume in the grinding process were obtained. The results show that the relative error between the theoretical value and the actual value of wear is 6.14%, which provides support for the prediction of workpiece surface morphology in the grinding process under different process parameters. In addition, an improved grinding heat model was established, and comprehensive research on the relationship between temperature, force, surface morphology and wear under different working conditions was studied.

A method for measuring and calculating the wear volume of the grinding process was proposed. The experimental results and simulation results were compared and analysed and provide a reference for the control of surface quality in...
the actual grinding process from the perspective of processing parameters.

The wear mechanism of the grinding process was studied, and the temperature field, wear volume and surface morphology were compared and analysed, which provides optimal machining parameters for improving the surface quality from the perspective of grinding burn and adhesive wear ($a_e = 0.02 \text{ mm}, v_w = 0.18 \text{ m/s} \text{ and oil-based grinding fluid}$).

In the future, the wear deviation caused by machine tool vibration will be considered.

**Author contribution** All authors contributed to the study conception and design. Modeling, simulation and paper writing were carried out by Cao Wei and Han Zhao, experiments and data processing were completed by Chen Ziqi, Jin Zili and Wu Jiajun and manuscript materials were sorted out by Qu Jinxiu and Wang Dong. All authors read and approved the final manuscript.

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**Declarations**

**Competing interests** The authors declare no competing interests.

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