Wheel wear-related instability in grinding of quartz glass

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Abstract
Grinding is a popular method for producing high-quality parts made of hard and brittle materials. A lot of researchers have focused on the impact of grinding parameters on surface quality. However, only a few studies discussed the surface quality instability caused by the grinding wheel wear during a long grinding process. In this paper, through wheel state monitoring and surface quality testing of ground samples, it is found that the relationship between ground surface roughness and theoretical undeformed chip thickness is significantly affected by the grinding wheel wear state rather than maintain steady as described in most available models. By introducing the normal grinding force, a linear relationship was found among normal grinding force, undeformed chip thickness, and ground surface roughness. Besides, sensitivity analysis was conducted to guide the parameter adjustment to maintain the stability of ground surface roughness and grinding state. The mechanism of the effect of wheel wear on normal grinding force was also studied in detail. This study will help to further understand the mechanism of the influence of wheel wear on the grinding stability.

Keywords Grinding stability · Wheel wear · Grinding force · Surface roughness

Abbreviations

\( a_p \) Depth of cut
\( C \) Number of cutting points per area
\( d_e \) Equivalent diameter of grinding wheel
\( D \) Diameter of the grinding wheel
\( E(R_a) \) Expected value of surface roughness \( R_a \)
\( E(t) \) Expected value of undeformed chip thickness
\( f \) Overlap factor
\( F_n \) Normal grinding force
\( h_w \) Reduction of abrasive grits protrusion height caused by grinding wheel wear
\( k \) Synthesized parameter of \( V_s, V_w \) and \( A_p \)
\( MRV_{41Cr4} \) Material removal volume of 41Cr4 in the preparation of wear grinding wheel
\( N_d \) Number of dynamic active grits
\( P_0 \) Constant determined by experiment
\( r \) Aspect ratio of the chip section
\( R_a \) Arithmetical mean roughness of grinding surface
\( S_w \) Tip area of the worn grit
\( t_m \) Maximum undeformed chip thickness
\( v_s \) Grinding wheel speed
\( v_w \) Workpiece infeed rate
\( \delta_{n,n+1} \) Change rate in normal grinding force between wear stage \( n \) and wear stage \( n+1 \)
\( \phi \) A coefficient fitted according to experimental data

1 Introduction

Grinding is considered as a high-efficiency and low-cost finishing operation [1]. It is a major manufacturing process that accounts for about 20–25% of the total expenditures on machining operations in industrialized countries [2]. It is also a vital technology for producing parts made of hard and brittle materials. Grinding is a complicated process viewed as the combination of several micro-machining processes performed by individual abrasive grits in the wheel [3]. The performance of ground parts is sensitive to the surface quality determined by the action of abrasive grits. During the grinding process, abrasive grits are wearing all the time, which results in the variation of the contact state between grinding wheel and workpiece. This variation leads to the instability of product quality.
To improve the stability of the ground surface quality, it is necessary to reveal the factors that dominate the surface quality. Surface roughness is a widely used and convenient parameter to characterize the ground surface quality [4, 5]. Many researchers focused on the effect of grinding processing parameters including the grinding wheel speed, workpiece feed rate, and depth of cut on the ground surface roughness. Malkin et al. [2] considered three grinding parameters and proposed a theoretical model to calculate the maximum undeformed chip thickness. Their model became the basis for many subsequent research works on grinding roughness prediction models. There are a lot of experimental studies to analyze the influence of processing parameters on the ground surface roughness [6–9], and these processing parameters are also the most widely used input parameters in regression [10, 11] and artificial intelligence analysis [12, 13] based on experimental data. Except for the processing parameters, some other parameters have been found to significantly affect the ground surface roughness. Agarwal et al. [14, 15] proposed a model to predict grinding surface roughness which considered the cross-section of scratch as a semicircle. In contrast, Sun et al. [16] considered the cross-section of abrasive grits as a parabola and modified the former model to obtain a new roughness prediction model. Liu et al. [17] presented a comprehensive study of a computationally efficient kinematic simulation to predict workpiece surface roughness in grinding using three different abrasive grit shapes (sphere, truncated cone, and cone). These researches showed that the cross-sectional shape of abrasive grits has a non-negligible effect on surface roughness. Besides, there are some other parameters, such as abrasive radius [18] and the height of the cutting edge [19], which also influence the ground surface roughness. These abrasive grit related parameters are sensitive to wheel wear and are unsteady during the grinding process. With the wear of abrasive grits, it is conceivable that the quality of the ground surface is continuously changing. However, few models can consider the influence of abrasive grit morphology caused by wheel wear. Moreover, the wear state of the abrasive grits is difficult to be monitored in real-time. To realize the stability of the grinding process and intelligent adjustment of processing parameters, it is important to find an intermediate parameter that reflects the effect of abrasive grit wear on the ground surface quality.

The continuous wear of the grinding wheel has a great impact on the machining results. There are several indirect approaches to detect the grinding wheel wear, such as optical methods [20, 21], wear reprography [22], acoustic emission (AE) signal [23, 24], and grinding force signal. Among the above methods, grinding force monitoring is a convenient method to detect the wear of grinding wheel. A lot of research results have shown that the wear of the grinding wheel has an influence on grinding force, so grinding force can be used for the detection and evaluation of the wear state of grinding wheel. Previous studies showed that an increase of grinding force signal is related to the wheel dulling [25]. Shen et al. [26] used the grinding force signal to monitor the grinding wheel wear. The grinding force ratio \( \frac{F_w}{F_t} \) was extracted from the force signal. When the grinding wheel was dull, the force ratio increased accordingly. Except for grinding force ratio, more characteristic parameters of the grinding force were studied by Kannan et al. [27]. They extracted the AR-8 coefficient, the mean wavelet level 1 approximate coefficient, and the correlation dimension from the grinding force signal. These characteristic parameters showed similar trends with the progress of wheel wear, and it was found that these parameters will increase with the wheel wear exacerbates. Zhang et al. [28] simulated the grinding process of abrasive grits, and the results showed that the grinding force was positively correlated with the contact area between abrasive grits and workpiece. This research was helpful to understand why the grinding force increases with grinding wheel wear progresses. Zhou et al. [29] studied the effects of the cutting edge radius on SiC chip formation and the grinding force. The result has shown that the grinding force changes as the grit radius getting bigger. These research results have shown that it is feasible to use the grinding force to characterize the grinding wheel wear.

Additionally, it is necessary to know whether the change in grinding force due to wheel wear has a significant effect on the ground surface roughness. Selvaraj et al. [30] studied the changes in cutting force and surface roughness with wheel wear. Their results showed that cutting force and surface roughness have similar trends with the wheel wear exacerbating when grinding metallic materials. In ceramic grinding, the grinding force and surface roughness have similar trends [31]. Zhu et al. [32] found a certain relationship between grinding force and machined surface roughness. Therefore, the normal grinding force could be used as the characteristic parameter of grinding wheel wear to learn the further relationship between wheel wear and ground surface roughness. However, how to use the grinding force to judge the wear state of the grinding wheel and predict the roughness more accurately remains to be studied.

With the development of artificial intelligence, intelligent manufacture will be an important form of processing in the future. To achieve the purpose, the grinding situation should be monitored online, and the wheel wear is then an important factor that affects the grinding quality. When the grinding wheel is worn and the shape of abrasive grits changes, the prediction results of the models that considering only processing parameters will have a large deviation. To fill this gap, how the normal grinding force and ground surface roughness change as wheel wear exacerbates is analyzed, and the grinding wheel wear is monitored by the normal grinding force. Through the
introduction of the normal grinding force, the wear factor is incorporated into the roughness prediction model to achieve a more accurate prediction result. Besides, the sensitive parameter that affects ground surface roughness and normal grinding force most under different wheel wear states is analyzed through ANOVA. Finally, the steady-state processing parameters that minimize the change in normal grinding force with the wheel wear increases are obtained through ANOVA and Duncan’s multiple range test.

2 Methodology

2.1 Experimental materials

The material of specimens used in this experiment was quartz glass. The quartz glass had a hardness of 5.5 HM, bending strength of 67 MPa, and elasticity modulus of 72 GPa, as presented in Table 1. The specimens had dimensions of 15 mm × 15 mm × 10 mm.

Table 1 The properties of the quartz workpiece used in the experiment

| Density (g/cm³) | Hardness (HM) | Bending strength (MPa) | Fracture toughness (GPa) | Elasticity modulus (GPa) |
|----------------|--------------|-----------------------|-------------------------|-------------------------|
| 2.2            | 5.5          | 67                    | 15.9                    | 72                      |

2.2 Experiment setup and conditions

The grinding experiment was conducted on a computer numerical control (CNC) milling machine NHM 800, 10 kW. Firstly, the specimens were glued on an iron block. Secondly, the iron block was clamped with a flat-nose plier. Thirdly, the flat-nose plier was fixed on the dynamometer, shown in Fig. 1.

An electroplated diamond grinding wheel with 80 grits was used in this experiment. The grit size was about 190 μm. The diameter and width of the grinding wheel were 20 mm and 20 mm, respectively. The grinding process was conducted without coolant. Suitable grinding parameters were selected based on existing related studies [33, 33, 33] and the working status of the milling machine. The levels of three grinding parameters are listed in Table 2.

In the long grinding process, grinding wheel wear will affect the stability of the grinding quality. However, the wear of grinding wheel is not obvious in a short time grinding of quartz. According to Zhao’s doctoral thesis [36], the wear rate is the fastest when grinding Cr-containing tool steel D3 (ISO) with large diamond abrasive grains. In order to appropriately accelerate the wear of the grinding wheel, 41Cr4 (ISO) was used as a workpiece to accelerate the wear of the grinding wheel. Therefore, before the quartz grinding test, the grinding wheel was used to grind a 41Cr4 steel sample to accelerate the wheel wear. The wheel speed was 5000 rpm, the workpiece feed rate was 200 mm/min, and the cutting depth was 50 μm when grinding the 41Cr4 sample. The topography of
the grinding wheel was measured before the glass was
ground. No clogging was observed on the wheel topog-
raphy, which eliminated the effect of clogging. When the
material removal volume of 41Cr4 steel (MRV_{41Cr4}) was
735, 3045, 29,295, and 50,295 mm³, the grinding
wheel was marked as stage 1, stage 2, stage 3, stage 4, and
stage 5, respectively. In different wear stages, grinding
experiments of quartz samples were carried out, and two
workpieces were ground without coolant for each set of
processing parameters. No dressing operation was con-
ducted during the experiment because of the low range of
dress ability of single-layer electroplated diamond grind-
ing wheel [37].

2.3 Measurement method

In different wear stages, the grinding wheel topography
was measured in a laser scanning confocal microscope
(KEYENCE VK-X260K). Five busbars were evenly cho-
sen on the cylindrical surface of the grinding wheel, and
three positions on each busbar were taken for the wheel
topography measurement, shown in Fig. 1. After the
wheel topography measurement, the grinding experiment
of quartz glass was performed.

During the grinding process, the grinding force was
measured using a piezoelectric dynamometer Kistler 9139
AA2, and the sampling frequency was set to 10 kHz to
collect the grinding force signal. Then the force signal
was subjected to Butterworth low-pass filtering with a
cut-off frequency of 2 Hz, and the mean and standard
deviation value of the force signal was calculated from
the filtered force signal.

After grinding, the surface roughness of the workpiece
was measured by a profilometer (Talysurf CLI2000).
Every workpiece was tested in 5 different positions. The
sampling length was randomly select to pre-measure the
roughness of the ground surface. Results showed that the
roughness was in the range of 3 to 9 microns. According to this result, the final sampling length was selected as
2.5 mm, and the data length was selected as 8 mm. The
topography of the ground surface was measured by a laser
scanning confocal microscope (KEYENCE VK-X260K) and a scanning electron microscope (FEI QUANTA 450).

3 Results and discussions

3.1 The influences of wheel wear on grinding force
and surface roughness

During the grinding process, the abrasive grits were con-
tinuously worn, showing an attrition wear, fracture, and
grits dropped out. At the same cutting depth, the greater the
wear, the larger the contact area between abrasive grits and
workpiece will be; thus, the grinding force increases with
abrasive grits wear [28].

The experiment data were shown in Table 3. The wear
of the grinding wheel affected the grinding force and the
state of abrasive grits, as shown in Fig. 2. As the wear
intensified, the grinding force increased, and the increasing
trend slowed down. In stage 2, the attrition wear of abrasive
grits was observed. In this stage, few grits were involved
in the processing, and most of the abrasive grits have
sharp edges. The normal grinding force was 35.11 N in
trial No. 2. In stage 3, the wear of abrasive grits gradually
exacerbated, which was manifested as the increase of the
wear area. Besides, the abrasive grit fracture and dropped
out occurred. These phenomena caused the abrasive cutting
to become blunt, which in turn led to an increase in the
grinding force. As the wear of the grinding wheel increased
to stage 5, the grinding force further increased.

Except for the grinding force and wheel topography, the
surface morphology of the ground workpiece also changed
according to the wheel wear, shown in Fig. 3. In stage 2, obvious groove marks and significant material fragmenta-
tion were observed because a small number of abrasive grits
with high protrusion height were involved in the processing.

With the wheel wear increase, the material was broken into
finer pieces in stage 3. When it came to stage 5, the grind-
surface tended to be flat, and the fragment became finer.

According to the maximum undeformed chip thickness
shown in Equation [2]

\[
t_m = \left[ \frac{6}{Cr \left( \frac{v_w}{v_s} \right) \left( \frac{a_p}{d_e} \right)^{\frac{1}{2}}} \right]^{\frac{1}{2}}
\]  

(1)

where \( t_m \) is the maximum undeformed chip thickness, \( C \) is
the number of cutting points per area, \( r \) is the aspect ratio
of the chip section, \( v_w \) is the infeed rate of the workpiece, \( v_s \) is the wheel speed, \( a_p \) is the cutting depth, and \( d_e \) is the equivalent diameter of grinding wheel.

Defining a grinding processing parameter-related factor

\[
k = \left( \frac{v_w}{v_s} \right)^{\frac{1}{2}} \frac{1}{a_p^2}
\]

then the maximum undeformed chip thickness is

\[
t_m = k \cdot \left( \frac{6}{C_T} \right) \cdot d_e^{-\frac{1}{2}}
\]

The parameter \( k \) is determined by three grinding parameters, which reflect the influence of processing parameters on the maximum undeformed chip thickness.

The normal grinding force increases with the aggravation of grinding wheel wear and has a non-linear positive correlation with \( MRV_{41Cr4} \), shown in Fig. 4a. On the contrary, the ground surface roughness has a non-linear negative correlation with \( MRV_{41Cr4} \) shown in Fig. 4b. All nine groups of parameters show similar trends. Before stage 3, the normal grinding force increases rapidly, and then, the normal grinding force increases slower as the wheel wear exasperates. On the opposite, the ground surface roughness decreases rapidly at first and then decreases slower as the wear aggravates. Therefore, the normal grinding force can be used to evaluate the wear state of the grinding wheel.

### 3.2 The influences of wheel wear on existing surface roughness prediction models

Roughness is an important characteristic parameter to evaluate the grinding quality. Surface roughness prediction models have attracted the attention of many scholars. Most researchers believe that the ground surface roughness is proportional to the undeformed chip thickness. The relationship is shown as Eq. (3) [14]:

\[
E(R_a) = \phi(1 - f)E(t)
\]

where \( E(R_a) \) is the expected value of surface roughness \( R_a \), \( \phi \) is a coefficient fitted according to experimental data, \( f \) is the overlap factor, and \( E(t) \) is the expected value of undeformed chip thickness which obeys a Rayleigh distribution.

This model is in good agreement with experimental results when the ground surface roughness is between tens of nanometers and a few microns [38][38]. However, this model did not consider the effect of grits wear. Considered that the wheel wear changes the distribution of maximum undeformed chip thickness, the relationship needs further research.

Figure 5 shows the relationship between surface roughness \( R_a \) and parameter \( k \). The linear fitting of \( R_a \) and \( k \) is
performed, and the $R$-square ($R^2$) values of the linear equations corresponding to the five wear stages are 0.01, 0.28, 0.29, 0.69, and 0.18, respectively. These $R^2$ values show that the linear relationship in all stages are not significant. As the grinding wheel wears, the distribution of undeformed chip thickness changes [38], and the relationship between $R_a$ and $k$ changes accordingly.

In existing research, it shows that there is a certain relationship between grinding force and machined surface roughness [32], but few studies have quantified this relationship. The topography and SEM photos of the ground surface (trial No. 2: $v_g = 500$ rpm, $v_w = 200$ mm/min, $a_p = 100$ μm) are shown in Fig. 3. The relationship between the normal force $F_n$, the surface roughness $R_a$, and MRV $40Cr$ under different trial parameters is shown in Fig. 4. The equation $k = (\frac{v_w}{v_s})^{1/2}a_p^{1/4}$ is determined by trial parameters. The International Journal of Advanced Manufacturing Technology (2022) 119:233–245.
relationship. The relationship among normal grinding force $F_n$, parameter $k$, and surface roughness $R_a$ is shown in Fig. 6. The data points are almost in a plane, showing a linear relationship among $F_n$, $k$, and $R_a$.

The relationship among normal grinding force $F_n$, parameter $k$, and surface roughness $R_a$ can be written as

$$F_n = a \cdot k + b \cdot R_a + c$$  \hspace{1cm} (4)

where $a$, $b$, and $c$ are the coefficients obtained by data fitting. The value of these coefficients and $R$-square (COD) is shown in Table 4. The $R$-square shows that the two-dimension linear relationship among $F_n$, $k$, and $R_a$ is valid. In addition, the value of the coefficient $a$ is positively related to $MRV_{41Cr4}$, so $a$ can be used to indicate the degree of grinding wheel wear.

In conclusion, three sets of processing parameters can be selected for pre-experiment to determine the relationship among $F_n$, $k$, and $R_a$ which is only related to the wear state of grinding wheel. Then, the ground surface roughness $R_a$ can be predicted by the normal grinding force $F_n$ and parameter $k$ during the grinding process.

### 3.3 Sensitivity analysis

In grinding process, as the wheel wear exacerbates, the surface roughness decreases. However, the grinding force increases with the wheel wear intensifies, which will increase the probability of surface quality instability. Therefore, the sensitivity analysis of the grinding process is helpful to ensure the stability of workpiece quality in a long-time grinding process.

#### 3.3.1 Sensitivity of surface roughness to grinding parameters

When the grinding surface roughness fluctuates or deteriorates, it is necessary to adjust the processing parameters to ensure the ground surface roughness meets demand. Theoretically, adjusting any of the three parameters can achieve the goal, but priority should be given to adjusting the most sensitive parameter.

Table 5 shows the $F$ value from ANOVA of ground surface roughness $R_a$ in different wheel wear stages. From the $F$ distribution critical value table, three critical values found that $F_{0.1}(2, 8)=3.11$, $F_{0.05}(2, 8)=4.45$, and $F_{0.01}(2, 8)=8.65$, and the significance is marked as “+,” “++,” “+++,” respectively.

When the grinding wheel is in stage 1, the effect of processing parameters on roughness is not obvious on 95% confidence level, as shown in Table 5. When the wheel wear reaches to stage 2, the workpiece infeed rate has a significant influence on the ground surface roughness. In stage 3 and stage 4, the wheel speed is the only parameter that has a significant influence. When it comes to stage 5, all the parameters have a great impact on ground surface roughness, and the depth of cut is the primary significant parameter, followed by workpiece infeed rate. Therefore, in different wear stages, the operator should give priority to adjusting the most significant parameters to make the grinding quality meets the requirements.

#### 3.3.2 Sensitivity of grinding force to grinding parameters

The increase of normal grinding force will increase the subsurface damage and the deformation of low stiffness parts. Therefore, the sensitivity of normal grinding force to grinding parameters should be analyzed to guide the adjustment of grinding parameters to reduce the grinding force.

Table 6 shows the $F$ value from the ANOVA results of the normal grinding force in different wear stages. The results show that the grinding wheel speed has a remarkable influence on normal grinding force in all wear stages. Before stage 2, the wheel speed is the only parameter that significantly affects the normal grinding force. With the wheel wear further increases, the workpiece infeed rate and depth of cut show a significant influence on normal grinding force. In order to reduce the grinding force, the operator should first consider increasing the wheel speed, followed by decreasing the cutting depth and then decreasing the infeed rate.

![Fig. 5 The relationship between surface roughness $R_a$ and parameter $k$ in different wear stages](image-url)
Fig. 6 The relationship among normal force $F_n$, parameter $k$, and surface roughness $R_s$ in different wear stages. Data in a all stages, b stage 1, c stage 2, d stage 3, e stage 4, and f stage 5.
Table 4: The value of fitting coefficients and $R$-square in different wear stages

| Factors | Stage 1 | Stage 2 | Stage 3 | Stage 4 | Stage 5 |
|---------|---------|---------|---------|---------|---------|
| $a$     | 3.26    | 3.92    | 6.48    | 7.59    | 13.11   |
| $b$     | 3.34    | -0.30   | -5.89   | -6.55   | 34.47   |
| $c$     | -38.85  | -12.81  | 20.10   | 46.58   | -115.90 |
| $R^2$   | 0.95    | 0.96    | 0.95    | 0.83    | 0.91    |

Table 5: The $F$ value from ANOVA of surface roughness $R_s$

| Factors                  | $F$ value |
|--------------------------|-----------|
|                        | Stage 1  | Stage 2  | Stage 3  | Stage 4  | Stage 5  |
| Wheel speed $v_s$        | 0.95     | 1.49     | 3.89 (+) | 3.67 (+) | 9.09 (+ + +) |
| Feed $v_w$               | 0.95     | 4.19 (+) | 2.76     | 0.98     | 14.53 (+ + +) |
| Cutting depth $a_p$      | 0.96     | 2.69     | 1.12     | 0.54     | 15.08 (+ + +) |

“+,” “++,” and “+++” indicate the significance level of $F$ test is 0.1, 0.05, and 0.01, respectively.

3.3.3 Sensitivity of grinding force to wheel wear

A long-term steady grinding state is beneficial to maintain the consistency of product quality. So, the sensitivity of normal grinding force to wheel wear needs to be further studied to maintain the steady grinding state for a longer time.

The change in normal grinding force is defined as

$$
\delta_{n,n+1} = \left| \frac{F_{n+1} - F_n}{F_n} \right|
$$

where $n$ and $n+1$ stand for different wheel wear stages, $n = 1, 2, 3, 4$.

If $\delta_{n,n+1}$ is the smallest under a certain set of processing parameters when the grinding wheel wear increases, the grinding state determined by this set of parameters is called steady-state parameters. While sensitive-state parameters appear when $\delta_{n,n+1}$ is the biggest. Table 7 shows the change in normal grinding force $\delta_{n,n+1}$ as the wheel wear exacerbates. Then ANOVA and Duncan’s multiple range test on $\delta_{n,n+1}$ is carried out to determine the sensitive state and steady state. The result is shown in Fig. 7.

Figure 7 shows that in early wear stage (before stage 2), the steady state of normal grinding force appears with the parameters that the grinding wheel speed is 1000 rpm, the workpiece feed rate is 500 mm/min, and the cutting depth is 50 μm. Then the steady-state changes to the parameters that the grinding wheel speed is 1000 rpm, the workpiece feed rate is 500 mm/min, and the cutting depth is 150 μm between stage 2 and stage 3. As the wear of grinding wheel further increases, the steady state gradually moves to the parameters that the grinding wheel speed is 5000 rpm, the workpiece feed rate is 500 mm/min, and the cutting depth is 150 μm. Considering maintaining the stability of normal grinding force, the grinding parameters should be set to steady-state parameters to minimize the change in grinding force.

The steady state is influenced by wheel wear. Henceforth, the mechanism of the influence of grinding wheel wear on the steady grinding state needs to be studied to deepen the understanding of the mechanism of grinding process. For a new grinding wheel, the protrusion height of abrasive grits is highly random, fewer effective abrasive grits are involved in grinding, and it is difficult to accurately characterize it by a certain distribution. (stage 1), shown in Fig. 8a. Due to the high randomness of abrasive grits protrusion height, the processing parameters that determine the steady state in this wear stage have no general regularity. As the wear intensifies, the protrusion height of abrasive grits can be described by a specific distribution. In this state, the parameters that determine the steady grinding state begin to show regularity (after stage 2). The mechanism of the sensitivity of grinding force to wheel wear in early stages (stage 2 ~ stage 3) and later stages (stage 4 ~ stage 5) needs to be studied to deepen the understanding of grinding mechanism.

When the grinding wheel is in early wear stages (stage 2 ~ stage 3), the number of effective abrasive grits involved in the grinding processing is less. Therefore, the reduction

Table 6: The $F$ value from the ANOVA of the normal grinding force $F_n$

| Factors                  | $F$ value |
|--------------------------|-----------|
|                       | Stage 1  | Stage 2  | Stage 3  | Stage 4  | Stage 5  |
| Wheel speed $v_s$        | 3.90 (+) | 4.61 (+) | 12.34 (+ + +) | 9.76 (+ + +) | 26.30 (+ + +) |
| Feed $v_w$               | 2.13     | 2.25     | 4.23 (+) | 7.40 (+ +) | 6.74 (+ +) |
| Cutting depth $a_p$      | 1.80     | 2.03     | 5.25 (+ +) | 7.60 (+ +) | 8.41 (+ +) |

“+,” “++,” and “+++” indicate the significance level of $F$ test is 0.1, 0.05, and 0.01, respectively.
of abrasive grits protrusion height caused by grinding wheel wear $h_w$ is significant, shown in Fig. 8. As a result, the grinding force generated by the parameters with a bigger actual cutting depth $a_a$ is less sensitive to grinding wheel wear. Because the actual cutting depth $a_a$ has a positive correlation with parameter $k$, the relationship between $\delta_{n,n+1}$ and $a_a$ can be qualitatively described by the relationship between $\delta_{n,n+1}$ and $k$. As shown in Fig. 9, with the increase of parameter $k$, the grinding steady state tends to be steady in early wheel wear stages (stage 2 ~ stage 3). It is consistent with the trend of experimental data analysis. However, when the wheel wear is severe (stage 4 ~ stage 5), the trend from experimental analysis is contrary to this theory. So, the mechanism should be further studied.

As the wheel wear intensifies, the frictional force on the wear plane of abrasive grits becomes the main component of grinding force. The normal grinding force component is shown as Eq. (5) [28]:

![Table 7 The change in normal grinding force $F_n$ when the wheel wear exacerbates](image)

![Fig. 7 The location of sensitive/ steady state of grinding force in different wear stages](image)

![Fig. 8 The change of abrasive grit protrusion height in different wear stages](image)
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The change in \( f_n \) (df\( _n \)) has a positive correlation with \( \delta_{n,n+1} \) because \( f_n \) is the main component of \( F_n \) when the wheel wear is severe. So, \( N_d \cdot v_w / v_s \) and \( v_w / v_s \) will have an influence on \( \delta_{n,n+1} \). Because \( N_d \) has a positive relationship with parameter \( k \), the relationship between \( \delta_{n,n+1} \) and \( N_d \cdot v_w / v_s \) can be qualitatively described by the relationship between \( \delta_{n,n+1} \) and \( k \cdot v_w / v_s \), shown in Fig. 10a, and the relationship between \( \delta_{n,n+1} \) and \( v_w / v_s \) is shown in Fig. 10b. The grinding state determined by parameters that have a smaller value of \( k \cdot v_w / v_s \) and \( v_w / v_s \) is less sensitive to the grinding wheel wear. This trend is confirmed by the experimental results.

Equation (6) shows that the force will be smaller when the grinding wheel continues to wear, and the stability of machining state and grinding quality can be maintained for a longer time, reducing the number of adjustments.

\[
f_n = \frac{4 \cdot P_0 \cdot S_w \cdot N_d \cdot v_w}{D \cdot v_s}
\]

where \( P_0 \) is a constant determined by experiment condition, \( S_w \) is the tip area of the worn grit, \( N_d \) is the number of dynamic active grits, \( v_s \) is the grinding wheel speed, \( D \) is the diameter of the grinding wheel, and \( v_w \) is the feed speed.

The wheel wear will cause variation in parameter \( S_w \) and \( N_d \). The total differential of \( f_n \) to the wheel wear \( w \) can be expressed as Eq. (7). The partial derivatives of \( f_n \) with respect to \( S_w \) and \( N_d \) are also calculated to analyze the sensitivity of grinding normal force to wheel wear. The wear area \( S_w \) can be treated as a constant when the state of the grinding wheel is determined, as shown in Eq. (8) and Eq. (9). So, \( N_d \cdot v_w / v_s \) and \( v_w / v_s \) are the key parameters of influence on the sensitivity of \( F_n \) to wheel wear:

\[
\frac{df_n}{dw} = \frac{\partial f_n}{\partial S_w} \cdot \frac{dS_w}{dw} + \frac{\partial f_n}{\partial N_d} \cdot \frac{dN_d}{dw}
\]

\[
\frac{\partial f_n}{\partial S_w} = \frac{4 \cdot P_0}{D} \cdot \frac{N_d}{v_s} \cdot \frac{v_w}{v_s}
\]

\[
\frac{\partial f_n}{\partial N_d} = \frac{4 \cdot P_0 \cdot S_w}{D} \cdot \frac{v_w}{v_s}
\]

The change in \( f_n \) (df\( _n \)) has a positive correlation with \( \delta_{n,n+1} \) because \( f_n \) is the main component of \( F_n \) when the wheel wear is severe. So, \( N_d \cdot v_w / v_s \) and \( v_w / v_s \) will have an influence on \( \delta_{n,n+1} \).

**Fig. 9** The relationship between the change in normal force \( \delta \) and \( k \)

**4 Conclusion**

In this paper, the influence of grinding wheel wear on grinding force and surface roughness is studied, and a semi-empirical roughness prediction model is proposed considering the influence of grinding wheel wear. To ensure the stability of the grinding process, sensitivity analysis was conducted to guide the adjustment of grinding parameters. The following conclusions are achieved:

1. The normal grinding force and ground surface roughness change with the grinding wheel wear exacerbates. The normal grinding force increases as wheel wear aggravates and the increase trend slows down. On the contrary, the ground surface roughness has a negative relationship with wheel wear, and the decrease trend slows down.

2. There is a linear relationship among the normal grinding force \( F_n \) parameter \( k \), and surface roughness \( R_a \). The coefficient \( a \) of the parameter \( k \) can be used to indicate the degree of the grinding wheel wear. The equation among \( F_n \), \( k \), and \( R_a \) can be determined by three pre-experiments, and the equation is only related to the wear state of the grinding wheel. Then, the ground surface roughness \( R_a \) can be predicted based on the normal force \( F_n \) and the parameter \( k \).

3. The sensitive parameter that affects ground surface roughness and normal grinding force the most under different wheel wear states is analyzed through ANOVA. In wheel wear stage 1, the effect of processing parameters on roughness is not obvious on 95% confidence level. When it comes to stage 2, the work-piece infed rate becomes the most significant parameter. After stage 3, the grinding wheel speed is the most sensitive parameter that influences roughness the most. As for normal grinding force, the grinding wheel speed is the most sensitive parameter in all wear stages.
The steady-state processing parameters are acquired through ANOVA and Duncan’s multiple range test. When the grinding parameters are set as the steady parameters, the change in normal grinding force can be minimized when wheel wear aggravates. The steady-state parameters alter as the wheel wear aggravates because the change rate of grit protrusion height, wear area, and the number of dynamic active grits varies in different wear stages.

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Data Availability The authors confirm that the data supporting the findings of this study are available within the article.

Declarations

Ethics approval This article has not been published or submitted elsewhere.

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