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Grinding of alumina ceramic with microtextured brazed diamond end grinding wheels

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Abstract
Brazed monolayer diamond grinding wheels have advantages of a high abrasive bonding strength, high protrusion, and a large chip disposal space. However, it is difficult to prepare ordered and fine-grained brazed diamond grinding wheels. This study presents a new method for grain-arranged, brazed diamond grinding wheels with microtextures with similar performance to ordered and fine-grained brazed diamond grinding wheels. First, coarse diamond grains (18/20 mesh) were orderly brazed to fabricate the end grinding wheels. Next, a series of microtextures were ablated on the diamond grains using a pulsed laser, and two types of textured end grinding wheels—TG-G (ablated microgrooves only) and TG-GH (ablated microgrooves and microholes)—were prepared. Then, an experiment involving the grinding of alumina ceramics was performed, and the grinding characteristics and grinding mechanism were analyzed. The results indicated that compared with untextured diamond end grinding wheels (TG), the textured diamond grinding wheels (TG-G and TG-GH) significantly reduced the grinding force and the roughness of the machined surface. The local stress concentration at the microtextures promoted the formation of microcracks in the diamond grains of TG-G and TG-GH, and the self-sharpening of the grinding wheel was significantly improved. The brittle fracture mode of ceramic materials in grinding included intergranular fracture and transgranular fracture. Ironing pressure action was a key material-removal mechanism. It had an important influence on the cutting force and plasticity characteristics of theTG machined surface. For the surfaces processed by TG-G and TG-GH, the effect of ironing was weakened, while shearing played a more important role. The TG-GH grinding wheel ablated with microgrooves and microholes was superior to the TG-G grinding wheel ablated with only microgrooves, with regard to the grinding force, roughness, and self-sharpening.

1. Introduction

The electroplated and resin bonded diamond wheels are widely used in precision grinding of hard and brittle materials. The preparation process of these two wheels is relatively simple, but the prepared wheels often have the shortcomings of a low bonding strength, easy dropping of abrasive grains, and low protrusion. The brazing method is a special method for preparing diamond grinding wheels. Brazing technology can help to form a chemical metallurgical bonding among diamond grains, a binder (brazing alloy), and a steel substrate, which makes brazed diamond wheels have high bonding strength with diamond grains, high protrusion, and large chip removal space [1,2].

The topography of conventional grinding wheels is inherently stochastic when referring to the cutting edge distribution, orientation, and protrusion, resulting in a small chip removal space, poor heat dissipation and surface defects (eg. Micro-fractures, burns and unfavorable residual stresses) [3,4]. Engineered grinding wheels are a kind of monolayer-abrasive grinding wheels, where abrasive grains are arranged in pre-defined positions. Due to the orderly arrangement of abrasive grains in engineering wheels, the number of abrasive grains can be greatly reduced and the chip space can be increased. Some studies show that compared with conventional grinding wheels, the engineering grinding wheels can effectively enhance heat dissipation, reduce the cutting temperature, and reduce the cutting force during the grinding process [5,6]. Some studies also show that the engineering grinding wheels can effectively improve the surface quality [7].

The grain-arranged brazed diamond wheel combines the engineering grinding wheels and brazing technology. This kind of...
grinding wheel, which has a large abrasive holding force, high protrusion of grains, large chip removal space, and good heat dissipation, has obvious advantages in grinding hard and brittle materials [8–10]. Using a fine-grained grinding wheel for semi-finishing and finish grinding is generally desirable to reduce the cutting force, improve the surface quality, and prevent the formation of cracks. The preparation of brazed diamond grinding wheels with ordered diamond grains has drawn much attention for its potential application in the precision grinding field. However, it is difficult to prepare ordered and fine-grained brazed diamond grinding wheels using the existing processes. In addition, the preparation of fine-grained brazed diamond grinding wheels produces microscale surface graphitizing layers, which affects the grinding performance of the grinding wheels. New solutions must be developed to address the preparation problem of brazed diamond grinding wheels with ordered fine grains.

Surface texturing, as one of the surface engineering technologies, has become a research hotspot in the field of surface engineering in recent years. Typical processing methods of surface texturing include laser processing, electrical discharge machining, ion beam machining, and electrodeposition. Laser ablation has the advantages of high energy density, high processing speed and high processing precision, and has become an important method for generating surface textures of refractory materials such as ablated diamond and cubic boron nitride [11]. According to the size of the texture, the surface texturing of the grinding wheel can be divided into macrotextures and microtextures. The formation of textures on the grinding wheel surface can enhance chip removal, increase heat dissipation, reduce surface damage, and reduce grinding force. Zhang et al. [12,13] presented a laser macro-micro combination structured grinding (LMMCSD) method to improve the surface quality and service life of grinding wheels. The experiment results of ceramic grinding indicated that the grinding force ratio and surface roughness were respectively 31% and 40% lower than those of conventional grinding wheels. Additionally, the LMMCSD method effectively reduced the wheel wear and workpiece subsurface damage. Butler-Smith et al. [14,15] used an Nd:YAG Q-switched pulsed laser to ablate array microstructures on CVD diamond film. Compared with a conventional electropolished grinding wheel, the grinding performances (i.e., wear, chip flow) and machined surface quality were highly improved. Guo et al. [16] presented a series of microstructured diamond wheels for optical glass surface grinding to improve the grinding performance. The experiments showed that the surface roughness and subsurface damage depth were both reduced with the decreasing interval of micro-groove arrays. Walter et al. [17] employed picosecond lasers to produce various micropatterns on the surface of grinding tools. Grinding experiments showed that all of the four textured grinding wheels had lower grinding forces than conventional wheels and the biggest reduction reached 54%. The above literatures show that textures significantly improves the grinding performance of grinding wheels. As far as we know, few reports have been made on the fabrication of a microtexture on the brazed grinding wheel with coarse diamond grains arranged in an orderly manner.

To obtain a novel wheel for precision grinding of hard and brittle materials, a new approach for grain-arranged brazed diamond end grinding wheels with microtextures is proposed in this study. First, coarse diamond grains are spatially arranged and brazed on an end grinding wheel, and then microtextures (microgrooves and microholes) are ablated on the surface of the diamond grains using a fiber pulse laser. The new brazed diamond end grinding wheels with microtextures were used for grinding difficult-to-machine alumina ceramic materials, and their performance was compared with that of an untextured grinding wheel. Grinding experiments were performed, and the grinding force, surface roughness, surface morphology, and diamond grain damage were analyzed. Finally, the grinding characteristics and mechanism were examined.

2. Experimental conditions and methods

2.1. Preparation of brazed end grinding wheels with ordered diamond grains

The abrasive material used in the experiment was MBS970 monocrystal diamond in complete crystal form, with a particle size of 18/20 # (850–1000μm). Fig. 1 shows the scanning electron microscopy (SEM) image of one diamond grain.

The substrate of the brazed diamond end grinding wheel is shown in Fig. 2a. The substrate material was 45# steel, the outer diameter of the end face was Ф31mm, and the inner diameter was Ф15mm. Diamond grits were arranged orderly on the end face of the grinding wheel and the grain volume fraction was about 25%. The number of diamond particles used was 161, and the density of the abrasive grits was approximately 0.279 grits/mm². The wheel substrate and diamond grits were first cleaned by ultrasonic washing, then a template with well-arranged holes processed by laser was used to arrange the diamond grains on the end face of the grinding wheel. Finally, a commercial Cu–Sn–Ti brazing alloy was used to braze diamond grits. The brazing temperature was 940 °C under the vacuum of 7.8 × 10⁻³Pa. Fig. 2b shows the brazed diamond grains on the grinding wheel. The exposed top faces of all diamond grains were nearly parallel to the end face of the grinding wheel.

2.2. Laser ablation of microtextures on surface of diamond grains

The brazed diamond end grinding wheel was first subjected to an end-face polishing process to remove the brazed materials covering the diamond surface. Then, the grinding wheel was ultrasonically cleaned. HT-20F fiber laser equipment (Zhongshan Hantong Laser Equipment Co., Ltd.) was used to ablate microtextures on surface of diamond grains. The working platform was adjusted by moving the X and Y axes, and the laser focal length was adjusted by moving the Z axis. The parameters of the laser ablation were as follows: a laser frequency of 30 kHz, a pulse width of 50 ns, and a scanning speed of 600 mm/s. The number of scans performed in the laser ablation for microgrooves and microholes was 100 and 500, respectively.

As shown in Fig. 3, two types of diamond grain microtextures were designed. Microtextures include microgrooves and microholes. The
interval between two microgrooves was 0.2 mm, and the microhole diameter was Ф0.02 mm. Fig. 3b involves only the ablation of microgrooves and the corresponding grinding wheel is denoted as TG-G. Fig. 3c involves the ablation of both microgrooves and microholes and the corresponding grinding wheel is denoted as TG-GH. An untextured grinding wheel is denoted as TG. Fig. 3d and e shows scanning electron microscopy (SEM) images of the microtextured diamond grains. After the diamond surface was ablated by the laser, microcubes were formed. Each microcube had four micro-edges. After the laser processing was complete, the size of the microcubes was approximately 150 μm × 150 μm, and the width of the microgrooves between adjacent microcubes was approximately 45 μm. After the laser ablation, the microholes were tapered, with an inlet diameter of approximately 45 μm and the depth of 150–200 μm.

2.3. Grinding experiment

The machine used in the grinding experiment was the MILLTAP 700 machining center, which had a maximum spindle speed of 24000 rpm. The workpiece material was alumina ceramic (Table 1). The ceramic workpiece (70 mm × 70 mm × 5 mm) was clamped on a vise fixture, which was mounted on a dynamometer (Kistler 9272) (Fig. 4). The dynamometer was used to measure the dynamic three-axis force and torque. The brazed diamond end wheel was mounted on a toolholder.

Two grinding experiments were performed (Fig. 4). The first experiment involved grinding a workpiece surface with a width of...
1.5 mm at four different feed rates, and the grinding forces of a single abrasive particle were measured during grinding. The distance between two adjacent abrasive particles in the outer ring of the grinding wheel was greater than 1.5 mm. When the workpiece was ground with the abrasive particles of the outer ring of the grinding wheel, the cutting force of a single abrasive particle can be measured. The second experiment involved grinding a workpiece surface with a width of 15 mm at four different feed rates, and the forces were measured during the grinding. SEM (NanoSEM430) was performed after grinding to examine the morphology of the machined surface and the damage of the diamond grains. Two surface profilers (LK-200H and Bmt expert) were used to detect the line roughness ($R_a$, $R_z$) and surface roughness ($S_a$, $S_z$), respectively. The grinding parameters were identical for the two experiments. The spindle rotating speed ($n$) was 5000 rpm, and the cutting speed ($v_c$) of the diamond grains was 480 m/min. The feed rates ($v_f$) were 100, 200, 300, and 400 mm/min. The single grinding depth ($a_p$) was 20 μm. Two-factor analysis of variance (ANOVA) at a 95% confidence interval was used for statistical analyses of grinding forces and surface roughness.

### Table 1

| Workpiece material | Alumina content | Fracture toughness ($K_{IC}$) | Compressive strength | Elastic modulus ($E$) | Vickers hardness ($H$) |
|--------------------|-----------------|------------------------------|----------------------|-----------------------|------------------------|
| Alumina ceramic    | 99%             | 3.83 MPa m$^{-1/2}$          | 8.43 GPa             | 375 GPa               | 18.5 GPa               |

![Fig. 4. Schematic illustration of the setup of grinding on the alumina ceramic.](image-url)
3. Experimental results

3.1. Morphology of diamond grains

Figs. 5–7 show SEM images of the diamond grains for the three grinding wheels TG, TG-G, and TG-GH. First, the situation of the diamond grains of the TG grinding wheel was analyzed. Microcracks formed gradually on the side edge of diamond grains after cutting for a certain period of time, and further block flaking occurred (Fig. 5a). After cutting for a long time, some diamond abrasive grains exhibited...
severe bulk flaking (Fig. 5). The diamond grain in Fig. 5b underwent transgranular fracture, which was related to the frequently occurring large mechanical load. A river pattern is clearly observed in the breakage area, which corresponds to cleavage fracture.

Next, the diamond abrasive grains of the TG-G and TG-GH grinding wheels were analyzed according to Figs. 6 and 7. After grinding for a certain period of time, the side edges of the TG-G and TG-GH abrasive grains suffered microcracks under the impact load, and the number of micro-damages was larger than that for the TG wheel. A single micro-damage may occur on one or several ablated microcubes. The micro-damage area was small, and microcracks were visible (Fig. 6a and b, Fig. 7a and b). After grinding for a long time, some diamond grains exhibited bulk flaking (Fig. 6c and d, Fig. 7c and d). The flaking zone was usually limited by the laser-ablated microgrooves, and the amount of flaking material was generally smaller than that for the TG grinding wheel. River patterns are observed in the flaking zones in Figs. 6d and 7d. Compared with the TG-G grinding wheel, the amount of micro-damage to the diamond grain edges of the TG-GH grinding wheel was larger. The fractures developed along the ablated microgrooves and holes, and microcracks were clearly observed around the holes. According to the foregoing analysis, the self-sharpening ability of the diamond grains of the grinding wheels increased in the following order: TG, TG-G, and TG-GH.

3.2. Grinding force

During the grinding process, the sequence of the grinding force measured by the i time pause during the machining was $F_{d-1i}$, $F_{d-2i}$, ..., $F_{d-ni}$ ($d = x$ or $y$). The effective mean force of each node was calculated using the following formula:

$$F_{d-var} = \sqrt{(F_{d-1i}^2 + F_{d-2i}^2 + ... + F_{d-ni}^2)/n}$$  \hspace{1cm} (1)

Fig. 8 presents a comparison of the grinding forces of the three end grinding wheels. The grinding force was significantly affected by the feed rate ($p > 0.05$) and the type of grinding wheel ($p > 0.05$). With an increase in the feed rate, the $x$, $y$, and $z$-direction forces and the resultant force of the three end grinding wheels exhibited an increasing trend. The change ranges of the resultant forces for the TG, TG-G, and TG-GH methods were [10.64 N–25.39 N], [7.50 N–13.36 N], and [5.32 N–12.35 N], respectively. The three component forces and the resultant force for TG were significantly larger than those for TG-G and TG-GH ($p > 0.05$). The three component forces and the resultant force for TG-G were significantly larger than those for TG-GH ($p > 0.05$). At a feed rate of $f = 100$ mm/min, the resultant forces of TG-G and TG-GH were reduced by 29.5% and 50%, respectively, compared with that of TG. At a feed rate of $f = 400$ mm/min, the resultant forces of TG-G and TG-GH were reduced by 47.4% and 51.4%, respectively, compared with that of TG.

Fig. 9 presents a comparison of the grinding force of a single diamond grain of the three end grinding wheels. Similar conclusions with regard to feed rate changes can be drawn. The three component forces and resultant force of the TG, TG-G, and TG-GH grinding wheels decreased in sequence, and their differences were significant. At a feed rate of $f = 100$ m/min, the resultant forces of TG-G and TG-GH were
reduced by 33.4% and 68.7%, respectively, compared with that of TG. At a feed rate of \( f = 400 \text{ mm/min} \), the resultant forces of TG-G and TG-GH were reduced by 43.7% and 67.7%, respectively, compared with that of TG.

Fig. 10 shows the grinding torque force \( M_z \) and grinding force \( F_x \) (\( v_f = 300 \text{ mm/min} \)) of a single diamond grain at each revolution period. During each rotation, the number of peaks in the torque force represented the number of diamond grains that participated in the cutting. There were nine peaks for each method. So it can be considered that the number of abrasive grains \( k \) involved in the cutting was 9 in all the cases, accounting for 13.8% of the outer-ring abrasive grains (65). Regardless of the torque force and grinding force \( F_x, F_y, \) or \( F_z \), the difference between the peak-to-peak values decreased in the following order: TG, TG-G, and TG-GH. The peak-to-peak difference was related to the uniformity of the abrasive grain edges. A smaller peak-to-peak value corresponded to a smaller mutual difference.

3.3. Surface roughness

The roughness of the machined surface is presented in Fig. 11. Fig. 11a and b shows the line-roughness values \( R_a \) and \( R_z \), which are used in most industrial inspections. Fig. 11c and d shows the surface-roughness values \( S_a \) and \( S_z \), which are used in some studies.

Fig. 11a shows the change in the roughness \( R_a \). As the feed rate increased, the average line-roughness \( (R_a) \) values for TG, TG-G, and TG-GH were in the ranges of [0.891 \( \mu \text{m} \)–1.419 \( \mu \text{m} \)], [0.714 \( \mu \text{m} \)–1.057 \( \mu \text{m} \)], and [0.603 \( \mu \text{m} \)–0.806 \( \mu \text{m} \)], respectively. Fig. 11c shows the changes in the average surface roughness \( (S_a) \). As the feed rate increased, the surface-roughness values for TG, TG-G, and TG-GH were in the ranges of [2.60 \( \mu \text{m} \)–5.79 \( \mu \text{m} \)], [1.98 \( \mu \text{m} \)–2.36 \( \mu \text{m} \)], and [1.60 \( \mu \text{m} \)–1.91 \( \mu \text{m} \)], respectively. The results indicate that the \( R_a \) and \( S_a \) values were significantly affected by the type of grinding wheel \( (p > 0.05) \). The \( R_a \) and \( S_a \) values for TG were significantly higher than those for TG-G and TG-GH \( (p > 0.05) \). At feed rates of \( f = 100 \) and 400 mm/min, compared with TG, the \( R_a \) values for TG-GH were reduced by 32.3% and 43.2%, respectively. At feed rates of \( f = 100 \) and 400 mm/min, compared with TG, the \( S_a \) values for TG-GH were reduced by 38.5% and 67.1%, respectively.

The roughness \( R_z \) and \( S_z \) were used to characterize the differences between multiple peaks and valleys. Fig. 11c shows the changes in the \( R_z \). As the feed rate increased, the \( R_z \) values for TG, TG-G, and TG-GH were in the ranges of [6.12–10.37 \( \mu \text{m} \)], [5.36–7.38 \( \mu \text{m} \)], [4.67–5.17 \( \mu \text{m} \)], respectively. The \( R_z \) value of TG was significantly greater than those for TG-G and TG-GH \( (p > 0.05) \). At feed rates of \( f = 100 \) and 400 mm/min, compared with TG, the \( S_z \) values for TG-GH were reduced by 38.5% and 67.1%, respectively.

The roughness \( R_z \) and \( S_z \) were used to characterize the differences between multiple peaks and valleys. Fig. 11d shows the changes in the \( R_z \). As the feed rate increased, the \( R_z \) values for TG, TG-G, and TG-GH were in the ranges of [6.12–10.37 \( \mu \text{m} \)], [5.36–7.38 \( \mu \text{m} \)], [4.67–5.17 \( \mu \text{m} \)], respectively. The \( R_z \) value of TG was significantly greater than those for TG-G and TG-GH \( (p > 0.05) \). At feed rates of \( f = 100 \) and 400 mm/min, compared with TG, the \( S_z \) values for TG-GH were reduced by 38.5% and 67.1%, respectively.
larger than those for TG-G and TG-GH ($p > 0.05$). However, at feed rates of 100 and 200 mm/min, the surface roughness $S_z$ for TG-G was greater than that for TG-GH. At feed rates of 300 and 400 mm/min, the surface roughness $S_z$ for TG-G was close to that for TG-GH. The difference between $R_z$ and $S_z$ should be related to the measurement method.

Fig. 12 shows the three-dimensional (3D) data obtained via the machined surface-roughness test. The peak value for TG was significantly higher than those for the other two methods. Large deep pits appeared on the surface processed by the TG grinding wheel. In contrast, small pits exhibited on the surfaces machined by the TG-G and TG-GH grinding wheels, and the pit depth was significantly smaller.

### 3.4. Surface morphology

Fig. 13a–e shows the SEM images of the machined surface of the TG grinding wheel after it was machined at a feed rate of 100 mm/min. The processed surface exhibited brittle fracture and plastic deformation areas. As shown in Fig. 13b–e, some grains had a brittle fracture surface or were broken or cracked, thereby causing the grain size to be smaller than the original value. This condition is a significant indicator of transgranular fracture. River patterns occurred in some fracture regions; this condition can be regarded as cleavage fracture. Fig. 13d clearly shows intergranular cracks and some complete grains, indicating intergranular fracture. Therefore, the fracture of the processed surface comprised intergranular and intergranular fractures. In addition, Fig. 13c and e indicate that the plastic deformation surface was very smooth. Squeezing marks and cracks, as well as powder debris (ultrafine grains), are observed on the smooth surface. Fig. 13f shows the SEM image of the processed surface at a feed rate of 400 m/min. Compared with the results of a low feed rate of 100 mm/min, the plastic deformation zone shown in Fig. 13f was significantly reduced, and the plastic deformation surface was also very smooth.

The surface brittleness and plasticity characteristics of TG-G and TG-GH were close to each other. Fig. 14a–d shows the SEM images of the TG-GH processed surfaces at a feed rate of 100 mm/min. The processed surface exhibited brittle fracture areas and plastic deformation areas. The brittle fracture modes of the machined surfaces comprised intergranular and transgranular fractures. Transgranular fractures exhibited features such as a brittle fracture surface, cleavage surfaces, broken grains, and cracks. The plastic deformation regions of TG-GH were smaller than those of TG. The plastic deformation areas of TG-GH exhibited plowing striations and grooves, in contrast to those of TG. Fig. 14e and f shows the SEM images of the TG-GH processed surface at a feed rate of 400 m/min. Compared with the results of Fig. 14a–d (low feed rate of 100 mm/min), the plastic deformation zone shown in
Fig. 14e and f was significantly reduced, and the degree of grain damage in the brittle fracture zone was significantly increased. The step transition surfaces can indicate the cutting contact information between the side edges of the diamond grains and the workpiece. Fig. 15 shows the SEM results for the step transition surfaces machined with the TG and TG-GH grinding wheels. As shown in Fig. 15b and c, the step transition surface of TG was relatively smooth, with some cracks. The step surface features are consistent with the features shown in Fig. 13. As shown in Fig. 15d and e, the step transition surface of TG-GH was not as smooth as that of TG, and it exhibited grooves. The step surface features are consistent with the features shown in Fig. 14. Therefore, the diamond grain side edges for TG should be blunt and smooth; the diamond grain side edges for TG-GH should be sharp and include some micro-chippings.

4. Discussion

4.1. Grinding geometric model

Fig. 16a shows the grinding geometric model of the end grinding. Some of the diamond grains cut into the workpiece. Each diamond grain is involved in cutting one layer of workpiece material via one of its side edges. The cutting material thickness of a single diamond grain during cutting is related to the feed rate per tooth (f). When the feed speed (v_f), the rotating speed (n), and the number of diamond grains involved in the cutting (k) are known, the feed amount per tooth (f) can be calculated as follows:

\[ f = \frac{v_f}{n k}. \]  (2)

The instantaneous change in the cutting material thickness of each diamond grain per revolution can be calculated using the following formula:

\[ h(\theta) = f \sin \theta. \]  (3)

Here, \( \theta \) represents the rotation angle of the diamond grain. When \( \theta \) is \( \pi/2 \), the maximum cutting material thickness is \( h_{\text{max}} = f \).

Fig. 16b shows the 3D cutting geometry. It corresponds to the cutting process of the \( m \)th diamond grain in Fig. 16a. One side edge of the diamond grain cuts along the cutting direction. This cutting process can be regarded as orthogonal cutting. The chip shape reflects the shape of the side edge of the diamond grain.

Fig. 16c shows the orthogonal cutting geometry of the \( m \)th diamond grain in Fig. 16a. The tool rake angle \( \alpha \) is negative. In the cutting direction and its vertical direction, the workpiece is subjected to two
component forces $F_t$ and $F_v$, respectively. Fig. 16c also indicates the principal stress in front of the cutting edge. Microcracks are easily generated and expand in the 45° direction during cutting.

Fig. 16d shows the cutting geometry perpendicular to the cutting speed direction, which corresponds to a section (XOZ) of Fig. 16a. The side edge of the diamond abrasive grains is composed of a straight edge and a small rounded corner. With the cutting parameters in this study, the cutting depth ($a_e$) was relatively small; thus, it is considered that only the circular arc part of the side edge cut the workpiece. The effective cutting material thickness of the side edge in Fig. 16d is $t$, and its relationship with the cutting material thickness $h$ is as follows:

$$t = h \sin \gamma$$  \hspace{1cm} (4)

When the effective cutting material thickness $t$ is smaller than a critical value $t_c$, brittle removal can be transformed into plastic removal \cite{18,19}.

$$t_c = \psi(E/H)(K_c/H)^2$$  \hspace{1cm} (5)

Here, $H$ represents the hardness, $K_c$ represents the fracture toughness, and $E$ represents the elastic modulus. Bifano et al. \cite{20} obtained the critical value of the brittle-to-ductile transition as follows:

$$t_c = 0.15(E/H)(K_c/H)^2.$$  \hspace{1cm} (6)

The force in cutting is further analyzed below. As shown in Fig. 16c, in the cutting direction and its vertical direction, the workpiece is subjected to two component forces $F_t$ and $F_v$. The $F_t$ and $F_v$ in Fig. 16d correspond to those in Fig. 16c. $F_t$ can be decomposed into $F_r$ and $F_z$ in the horizontal and vertical directions. Owing to the existence of $F_z$, there is a component force pressing on the workpiece surface during the grinding process. The relationships among $F_t$, $F_r$, and $F_z$ are as follows:

$$
\begin{align*}
F_t &= F_r \sin \gamma \\
F_z &= F_r \cos \gamma \\
F_v &= F_z
\end{align*}
$$  \hspace{1cm} (7)

Fig. 16e presents a schematic of the 3D forces of the diamond grain. According to Fig. 16d, when the rotation angle is $\theta$, the diamond grain is subjected to 3D forces $F_t$, $F_r$, $F_z$. $F_r$, $F_z$, and $F_v$ can be further decomposed into the $x$, $y$, and $z$ components as follows:

$$
\begin{align*}
F_t(\theta) &= -F_t \sin \theta - F_r \cos \theta \\
F_r(\theta) &= F_r \cos \theta - F_z \sin \theta \\
F_z(\theta) &= F_z
\end{align*}
$$  \hspace{1cm} (8)

The cutting material thickness of a single diamond grain is the largest at $\theta = \pi/2$.

In actual grinding, $k$ diamond grains cut into the workpiece at different positions, and the forces in the $x$, $y$, and $z$ directions can be calculated using the following formula:

Fig. 11. Roughness comparison of the machined surfaces. (a) $R_a$, (b) $R_z$, (c) $S_a$, and (d) $S_z$. 

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Since the end grinding and end milling are essentially the same, the milling force prediction method in the literature [21] can also be used for end grinding. First, on the basis of the measured force, the properties of the cutting edge's micro-elements and the micro-element force are deduced. Then, a calculus algorithm can be established by using Equations (7)–(9) to predict the grinding force under other cutting parameters. However, the algorithm should consider complicated random factors, such as the changing conditions of the abrasive grains after self-sharpening, the uneven size of the abrasive grains and the inconsistent side edges. This study will not discuss these factors further. Equations (7)–(9) are mainly used to qualitatively analyze the characteristics of the cutting forces and stresses.

4.2. Grinding characteristics and grinding mechanism

It is generally believed that diamond grinding wheels have the characteristics of “self-sharpening,” which can keep the abrasive grains sharp and facilitate further grinding. Abrasive “self-sharpening” is essentially a self-rupture of the abrasive grain under the action of an external load, forming a new sharp cutting edge. The diamond abrasive grains of the TG, TG-G, and TG-GH grinding wheels ruptured on the side edges that played a cutting role. River patterns and lamellae appeared in the ruptured zones of the abrasive grains of the three types of grinding wheels. This is a typical sign of cleavage fracture in transgranular fracture. Therefore, cleavage fracture is an important fracture mode common to the diamond grains of the three types of grinding wheels. The (111) plane of the monocrystal diamond was a cleavage plane. Because the (111) plane was an effective atom close-packed plane, the weaker bonds between the planes were more likely to break under external forces. Therefore, the diamond abrasive grains tended to cleave along the (111) plane. There were differences in the fracture characteristics of the three grinding wheels. For the TG grinding wheel, the load required for local brittle fracture to occur throughout the diamond was large. When breaking, it is easy to form large pieces of material to peel off, which makes it difficult to achieve uniformity among diamond abrasives. For the TG-G and TG-GH grinding wheels, every diamond grain was cut into microcubes by ablating microgrooves. Material fractures developed in the microgrooves and were bordered by other microgrooves, and the amount of material that was peeled off at a single time was often small, which made the uniformity among diamond abrasives better.

The reasons for the local material fracture of the diamond grains must be analyzed according to the force and stress. Examine the diamond grain at position A in Fig. 16a. The tangential force (Y direction) of this diamond grain has an extreme value. For the case of \( v_f = 100 \text{ mm/min} \), according to the extreme value of the tangential force and the effective cutting material area, the rake face extreme stresses of the diamond grain side edges for TG, TG-G, and TG-GH were calculated as 9.8, 6.62, and 5.63 GPa, respectively. Excluding friction and other influences, the extreme stress of a grinding wheel per revolution may be close to the compressive strength of diamond (8.43 GPa), which is a prerequisite for the formation of microfractures in diamond side edges. Under repeated interrupted cutting, impact fatigue occurred, gradually causing the side edges of the diamond grains to crack.

The cutting forces for TG-G and TG-GH were significantly smaller than that for TG (Section 4.2). However, the self-sharpening was better.
for TG-G and TG-GH (Section 4.1), which was closely related to the special self-sharpening mechanism. When the microtextures were ablated, the area of the top surface of the diamond grains for TG-G and TG-GH was significantly smaller than that for TG (Fig. 17). The cutting contact area was reduced. Typically, under the action of an external force, several microcubes of the diamond grains of TG-G and TG-GH (not the entire diamond grains) bore most of the grinding force. Therefore, several microcubes were locally subjected to relatively high stress. Additionally, the four micro-edges of the laser-ablated microcubes were not processed via edge grinding, and they were uneven and included some micro-chippings. Under the external load, the sharp corners and some protrusions were subject to very high stresses \cite{22,23}. These factors resulted in a stress concentration phenomenon, promoted the formation of dislocations in the microcubes of the diamond grains, and promoted the formation of microfractures with a smaller cutting force. Therefore, TG-G and TG-GH had more sharp micro-edges, and their self-sharpening was significantly better than that of the TG method. TG-GH ablated not only a series of microgrooves but also a series of microholes. In addition to microgrooves, microholes cause stress concentration. Thus, TG-GH had more micro-edges and better self-sharpening than TG-G.

During the cutting process, the cutting forces of TG, TG-G, and TG-GH decreased sequentially. This condition was closely related to the ironing pressure action and self-sharpening. Ironing may occur during

Fig. 13. SEM images of the TG processed surface. (a–e) \( v_f = 100 \text{ mm/min} \), and (f) \( v_f = 400 \text{ mm/min} \).
metal cutting when the thickness of the cutting material is small [24].
In this study, some evidences indicated that the grinding of brittle
materials also had an ironing effect. Fig. 18 shows the schematic model
of ironing pressure action. The ironing pressure action has relations
with the cutting edge blunt radius. When the cutting edge blunt radius
of the diamond grain increases, part of the workpiece material is ironed
into the flank face (Fig. 18a) and squeezed and rubbed by the flank face
and workpiece. As shown in Fig. 18b, the direction of the maximum
shear stress ($\tau_{\text{max}}$) and the direction of the principal stress are 45°,
and the shear direction of the separation point between the chip and the
workpiece is consistent with the direction of the cutting speed. There-
fore, the thickness of the material being ironed can be expressed as
$$\Delta \alpha \approx r_\delta (1 - \cos 45).$$  
(10)

Usui [24] gave an approximate expression of the ironing pressure
force during metal cutting, which can be used for qualitative analysis in
this study. The expression is as follows:

$$p_0 = \psi(\delta)(H_b/100)^2 + \sin(\delta/2 + \rho) \times (\sqrt{1 + \mu^2} / (2 \sin \delta))(H_b/100)$$
$$\psi(\delta) = (\sin \delta/\delta + \sin \delta)/(1 - \sin \delta/2)(1 + \mu/(1 - \sin \delta/2)/\cos \delta/2).$$

(11)

where $p_0$ represents the ironing pressure force, $\mu$ represents the friction
coefficient, $H_b$ represents the Brinell hardness of the workpiece, $\rho$ re-
presents the cutting edge blunt radius, and $\delta$ represents the cutting
angle.

The above-mentioned ironing model and equations indicate that the
blunt radius of the cutting edge is the important condition to form

Fig. 14. SEM images of the TG-GH processed surface. (a–d) $v_\ell = 100 \text{ mm/min}$, and (e–f) $v_\ell = 400 \text{ mm/min}$. 
ironing. As the cutting edge blunt radius increases, the probability of ironing increases. Especially when the cutting edge blunt radius is close to or greater than the effective cutting material thickness, the difficulty of forming the initial microcracks on the workpiece material in front of the tool tip significantly increases, causing the workpiece material to be easily ironed into the flank face. Under the cutting parameters in this study (n: 5000 rpm, vf: 100–400 mm/min, k: 9), it could be calculated based on Equations (2) and (4) that the maximum effective cutting material thickness was in the range of 1.92–7.70 μm. Regarding the bottom of the side edges of the diamond grains, which was directly related to the surface of workpiece (see Fig. 16d), the effectively cutting material thickness will be less than the calculated values. The diamond grains were not treated by the grinding; therefore, the blunt radius of the sides edges of the grains is likely to close to or greater than the effective cutting material thickness. All these are the prerequisite for the formation of ironing in the process of grinding ceramics with brazed diamond end grinding wheels.

Equations (10) and (11) can be used to explain why the TG grinding force was significantly larger than the TG-G and TG-GH grinding forces in the comparison experiment for the cutting force of a single diamond grain. The cutting edge of the diamond grain of the TG grinding wheel had a large blunt radius under the initial conditions. Subsequently, a large blunt radius was maintained owing to poor self-sharpening during grinding. According to Equation (10), when the cutting edge blunt radius increases, more materials entered the flank face during ironing, and the tool–workpiece friction was considerable. According to Equation (11), when the cutting edge blunt radius and friction coefficient increased, the ironing pressure force increased significantly. In comparison, the cutting edges of the diamond grains of the TG-G and TG-GH grinding wheels were sharper, and their cutting edge blunt radii were smaller. A stress concentration phenomenon was formed in front of the tool tip. Therefore, only a small force was needed to generate a large concentrated stress, and initial shear cracks were formed in front of the tool tip, cutting the workpiece crystal grains (Fig. 16c). According to Equations (8) and (9), the grinding force of the end grinding wheel was superimposed by the forces of the multiple diamond grains involved in cutting; thus, the grinding force of the TG grinding wheel was greater than those of the other two types of grinding wheels. Compared with TG-G, TG-GH had better self-sharpening performance, and more micro-edges were generated during grinding. The greater the number of micro-edges, the smaller the cutting force [25]. Therefore, the cutting process of TG-GH was more relaxed, and the cutting force was smaller.

Fig. 19 further analyzes the grinding force characteristics of a single diamond grain. According to Fig. 16c and d, Fv is equivalent to the tangential force Ft, Fv is equivalent to Fx, and Fv can be regarded as $F_v = \sqrt{F_t^2 + F_x^2}$. Based on the grinding force data of single diamond grain (Fig. 9), Fig. 19 shows the ratio of the grinding force Fv to the grinding force $F_t$. The $F_v/F_t$ values of TG-G and TG-GH were significantly larger than that of TG. The ratio of $F_v/F_t$ can be considered as the reciprocal of the wheel–workpiece friction coefficient [26]. Therefore, the friction coefficient for TG was significantly larger than those for TG-G and TG-GH. This finding provides strong evidence for the mechanism of ironing pressure action of brittle materials shown in Fig. 18.
The surface roughness is an important index for grinding products. At four feed rates, the surface roughness was significantly smaller for the TG-G and TG-GH methods than for the TG method. This can be analyzed with regard to three aspects. First, the laser ablation of microtextures on diamond grains was equivalent to a significant reduction in grain size. Second, after the microtextures were ablated, the self-sharpening of the abrasive grains was improved, the number of micro-edges formed was large, and the micro-edges were very sharp; thus, the cutting force was smaller, and the grinding stability was better. Third, after the microtextures were ablated, the abrasive grains were slightly broken in microcubes to avoid large pieces of damage, resulting in good uniformity between the diamond grains and small differences in the peak-to-peak values of the grinding force (Fig. 10). All three aspects were beneficial for reducing the average surface roughness. Compared with the TG-G method, the surface roughness was lower for TG-GH. This is because the TG-GH method had better self-sharpness, yielding the formation of more micro-edges, better uniformity between abrasive grains, smaller cutting forces, smaller differences in the cutting force peak-to-peak values, and higher cutting stability.

Whether the cutting process for a brittle workpiece material is brittle or ductile is often related to the material thickness. The cutting material thickness can be calculated using Fig. 16 and Equations (2)–(5). As shown in Fig. 16b, the diamond grain at position A had the largest cutting thickness and tangential force. The processing parameters were as follows: \( n = 5000 \text{ rev/min} \), \( k = 9 \), and \( \alpha_{e1} = 20 \mu m \). When \( v_f \) was 100 mm/min, the calculation results were \( f = 2.22 \mu m \), \( h_{max} = 2.22 \mu m \), and \( t = 1.92 \mu m \). When \( v_f \) was 400 mm/min, the calculation results were \( f = 8.89 \mu m \), \( h_{max} = 8.89 \mu m \), and \( t = 7.7 \mu m \). By substituting the material property value of the workpiece into Equations (6) and (7), the critical value of the brittle-to-ductile transition (\( t_c = 0.13 \mu m \)) was calculated. Clearly, the values of the effective cutting material thickness (1.92 and 7.7 \( \mu m \)) were significantly larger than the critical value of the brittle-to-ductile transition (0.14 \( \mu m \)). Therefore, the cutting process for all three types of end grinding wheels

![Grinding geometric model](image)

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**Fig. 16.** Grinding geometric model. (a) grinding ceramics with the end grinding-wheel, (b) 3D cutting geometry of the diamond grain in point A, (c) orthogonal cutting geometry, (d) cutting geometry view in a plane normal to the cutting direction, and (e) cutting forces in XY plane.
from 100 to 400 mm/min was a brittle mode. This is confirmed by the SEM results for the processed surfaces (Figs. 13–15). The surfaces processed by these three types of grinding wheels have more brittle fracture zones and some plastic zones. The surface characteristics of TG-

Fig. 17. Comparison of the effective top surface areas of the diamond grains in the three grinding wheels.

Fig. 18. Mechanism of ironing pressure action.

Fig. 19. Grinding force ratio ($F_v/F_t$) for a single diamond grain.
G and TG-GH were relatively close. The reasons for the formation of TG and TG-GH processed surfaces are discussed below.

Both the TG and TG-GH processed surfaces showed some brittle fracture zones. Alumina ceramics have a polycrystalline structure composed of ionic or covalent bonds with a low fracture toughness. Under an external load, the stress causes microcracks on the workpiece surface, which expand rapidly and cause brittle fracture. The brittle fracture zones for the two processing methods included intergranular and transgranular fractures. Under the brittle cutting mode, cracks may be generated and propagated as shown in Fig. 16c and d. Cutting shear and extrusion caused high density dislocations (Fig. 16c). After these actions reached a certain level, intergranular fractures and transgranular fractures occurred. When the thickness (t) of the cutting material was greater than \( t_e \), median cracks were prone to occur in the \( F_d \) direction and promoted the fractures of the workpiece surface in the subsequent processing (18) (Fig. 16d). In addition, the larger friction between the flank and workpiece can also induce tensile stress and promote the fractures of the workpiece surface [27]. When transgranular fracture occurred, the surface was prone to brittle fracture, cleavage, broken crystals, and cracks. After intergranular fracture, the grains were easily pulled out. For TG, the side edges of diamond grains were relatively blunt, and the cutting load was large. Both the greater extrusion force and friction force may induce more fractures and cause the grains to easily pull out as large blocks (green dotted lines in Fig. 16c). Thus, large deep pits occurred (Figs. 12a and 13b), and the surface roughness was large. The diamond grains of the TG-GH grinding wheel exhibited good self-sharpening and sharper cutting edges. Even if the load was relatively small, a large stress can form in the front of the sharp cutting edge, which can lead to easy transgranular fracture. Under a small load, the grains were not easily pulled out in large blocks (blue dotted lines in Fig. 16c), the pits formed by the grain extraction were small and shallow (Figs. 12c and 14b), and the surface roughness was very low. In addition to the grinding wheel method, the feed rate also had a greater impact on the fracture zone of the processed surface. Higher feed rates will cause more surface fracture zones (Figs. 13f, 14c and 14f). When the feed rate was increased, the amount of material in a single cut increased significantly, causing the dislocation density in the front of the cutting edge and cutting force to increase significantly. This condition further caused the area and depth of the fracture zone of the processed surface to increase.

Compared with TG-GH, the TG processed surface had more ductile regions and was smoother. Cracks perpendicular to the cutting direction and some residual fine powders were also observed on the processed surface of the TG grinding wheel (Fig. 13). The processed surface of TG-GH had plowing striations and grooves, with fewer cracks and residual fine powders (Fig. 14). These phenomena are related to the material removal mechanism. The diamond grains in the TG grinding wheel had blunt side edges, and the blunt radius of the cutting edge was large. Part of the workpiece material entered the contact interface between the flank face and workpiece through the ironing action as shown in Fig. 18. A strong local stress field can form between the flank and the workpiece. The stress field was composed of a hydrostatic compressive stress that was superimposed by a shear stress and a tensile stress that was induced by frictional force at the diamond abrasive grain–workpiece interface. With the shear stress, dislocation movement and bond rupture occurred, thereby pulverizing the workpiece surface material. Hydrostatic pressure further recompacted the pulverized material [28]. In this way, the surface materials of the workpiece were transformed into fine grains and compacted to form a smooth plastic surface. Under tensile stress [27,29], a series of cracks perpendicular to the cutting direction were formed (Figs. 13c and 15c). By contrast, the side edges of the diamond grains of the TG-GH grinding wheel were relatively sharp and included a few micro-chippings. Stress concentration was formed on the tip of the sharp cutting edge; as a result, transcrystalline fractures easily occurred. A few plastic areas, including plowing striations and grooves, easily formed (Figs. 14d and 15e). Thus, the ironing effect of the TG-GH grinding wheel was weakened, while the shearing effect was more obvious. Since the cutting edge contained some micro-chippings, the plastic zones of the TG-GH processed surface were reduced compared to the TG method. The above analysis provides additional important evidence for the mechanism of ironing pressure action in Fig. 18.

5. Conclusion

With the use of vacuum brazing technology and laser ablation technology, two microtextured brazed diamond end grinding wheels (TG-G and TG-GH) were prepared and compared with an untextured grinding wheel (TG) for grinding alumina ceramics. In accordance with the results, the following conclusions are drawn.

(1) The grinding forces and peak-to-peak value differences of the grinding forces for the three grinding wheels decreased in the following order: TG, TG-G, and TG-GH. The three grinding wheels exhibited significant differences.

(2) The surface roughness decreased in the following order: TG, TG-G, and TG-GH. The surface roughness values for TG-G and TG-GH were significantly smaller than that of TG.

(3) The grinding force and surface roughness were significantly affected by the feed rate (\( p > 0.05 \)) and the type of grinding wheel (\( p > 0.05 \)).

(4) The self-sharpening performance increased in the following order: TG, TG-G, and TG-GH.

(5) Local stress concentration was generated on the microtextures of the diamond grains, and more microcracks were formed under a smaller load. This condition was the main mechanism underlying the improvement of the self-sharpening performance of the textured grinding wheel.

(6) Ironing pressure action was a key material-removal mechanism and had an important influence on the plasticity characteristics of the TG machined surface. For the surfaces processed by TG-G and TG-GH, the effect of ironing was weakened, while shearing played a more important role.

(7) The TG-GH grinding wheel with microgrooves and microholes was superior to the TG-G grinding wheel, which has only microgrooves, in terms of grinding force, roughness, and self-sharpening.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ceramint.2020.05.009.
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