Experimental investigation on granite cutting by means of diamond frame saw

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Received: 29 August 2021 / Accepted: 25 October 2021 / Published online: 9 November 2021
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Abstract
A series of sawing experiments on granite was carried out to explore the cutting performance of a diamond frame saw with the horizontal reciprocating cutting mode. A model of the average thickness of the cutting chip was established and the characteristics of cutting forces were analyzed. The wear mechanism of segments was revealed by analyzing the width of the saw kerf and the wear morphology of the diamond segments. The results demonstrated that the wear resistance and the cutting forces increased with the feed speed. The cutting forces changed abruptly at the reversing point during granite cutting. Meanwhile, the proportion of macro-fractured and pulled-out diamond particles and the mean wear rate of segments increased with the feed speed, and the mean protrusion height of diamond particles was less than 100 μm. The width of the saw kerf reduced gradually during the sawing progress, forming a cone that is wide at the top and narrow at the bottom. Furthermore, the investigations proved that the wear of the segments remains consistent in two directions (y, z). An increasingly apparent phenomenon of protruding diamond particles appears on the side surface of the segment with the increase of feed speed. The research can provide certain data support for granite cutting and lay the foundation for the subsequent optimization of the equipment.

Keywords Diamond frame saw · Granite cutting · Diamond particles · Wear morphology · Saw kerf

1 Introduction
With the vigorous development of architectural decoration, precision machinery, and other industries, natural stones are widely used because of their great appearance and stable performance. The sawing equipment such as diamond circular saw, frame saw, and wire saw which has caught widespread attention have been applied in sawing natural stones. Granite is a type of material with high hardness and brittleness, and realizing its high-efficiency sawing has become an important direction in hard stone processing. The efficiency of stone processing equipment is affected by many factors, such as the performance of cutting tools, the hardness of processed materials, and so on. At present, the cutting forces and tool wear are used as the evaluation indexes of sawing performance by most scholars. Many scholars have conducted research and analysis on the cutting forces in order to study the sawing mechanism. Turchetta [1] built the cutting forces model of the diamond particle and measured the cutting forces under various processing conditions. The function relation between cutting forces and average sawing chip thickness was obtained by regression analysis. Xu et al. [2] studied the chips in the process of sawing granite. The result showed that the normal force of each particle increases with the maximum undeformed thickness of the chip. Polini and Turchetta [3] conducted a quantitative analysis of chips by establishing the cutting forces model. The model showed that the cutting depth has a significant effect on the cutting forces. Huang et al. [4] proposed a prediction model of sawing power based on the tangential forces, and they validated and modified the model through experiments of the diamond circular saw. This model provides the references for optimizing sawing.
parameters and reducing energy consumption. Bayram and Tumac et al. [5, 6] deduced a model to predict the cutting performance of sawing tools, which indicated that the cutting forces are closely related to the type of stone. Schulze et al. [7] established a multiple regression model for kinematic simulation, which provides guidance for the calculation of the size and direction of the forces in milling. Gelfusa and Turchetta [8] used a single diamond-coated bead to cut granite and established a model of the cutting force components. The results showed that cutting forces increase with the feed speed. Wang and Clausen [9] found that the forces of cutting depend on the sawing position, sawing direction, sawing path, cutting depth of per grit, and coolant. Simultaneously, Wang et al. [10] simulated the sawing forces of the saw blade, segments, and diamond particles during sawing; the results showed that the feed speed and cutting performance determine the sawing force and segment wear.

To optimize the processing performance of the sawing tools, the wear of diamond segments was studied by many scholars. A set of methods for measuring the macroscopic geometric wear of diamond tools were established to characterize the wear of diamond tools by Polini and Turchetta [11, 12]. Besides, the forces and acceleration signals in three directions under different processing conditions were collected for signal processing analysis and the results showed that the forces and acceleration signal feature can provide an effective mean for real-time monitoring of the tool wear. Di Ilio et al. [13, 14] proposed a theoretical model of tool wear. The model indicated that the diamond particles must maintain the proper shedding rate to keep self-sharpening, and the matrix must wear at the proper wear rate as well. Wear characteristics of diamond with a circular saw during the granite sawing and a load model of combination saw were studied by Zhou et al. [15]. Their study showed that uneven load is the main factor leading to the inconsistent wear of combined segments. The equivalent chip thickness models were established by Konstanty and Tyrala [16, 17]. The models expressed the relationship between sawing efficiency and tool life. They also investigated the effect of martensite transformation on the wear behavior of iron-based diamonds and found that the diamond concentration is the main factor affecting the wear rate. Bayram and Kulaksiz [18] established a new diamond segment unit wear model to evaluate the sawing performance. The determination coefficient of the regression equation is determined based on experimental data that tested on the diamond frame saw. The model showed that the wear of diamond segments is proportional to the feed speed. In addition, Aydin et al. [19–22] carried out a series of sawing experiments using circular diamond saw blades. In their study, the specific energy, noise, and saw blades wear performance models for granitic rocks sawing were established and validated. The models provided the theoretical basis for the selection of process parameters and optimization of sawing.

Most of the literature focuses on the diamond circular saw and the diamond wire saw, with few references related to diamond frame saws. However, diamond frame saws are also worthy of attention because of the advantages of high processing efficiency, great processing quality, low noise, and dust pollution [23], which is especially suitable for sawing large-size slabs. The diamond frame saw realizes the stone blocks sawing in the reciprocating motion of the diamond segments, the diamond segments are welded on the saw blades and the saw blade is tensioned on the saw frame. The reciprocating movement results in a harsh machining environment and increases the wear of the diamond segments, which leads to a decrease in sawing efficiency and precision. In order to solve these problems, scholars have conducted a series of researches on diamond segments. Li et al. [24] established a mathematical equation for optimal system parameters based on the studies of the sawing motion mechanism, providing the basis for the sawing motion trajectory design. Wang and Rolf [25] obtained the wear and cutting forces of diamond segments under various machining through the sawing experiments. The results indicated that the sawing forces and segments wear are determined by the feed speed and sawing performance. Sun et al. [26] established a model between the characteristics of processed rock and wear through experiments. Wang et al. [27] analyzed the segments’ wear with different compositions of a matrix under two sawing modes. The results showed that the wear rate of the iron-based segments is higher than that of the cobalt-based segments. Compared with the diamond frame saw, the matrix tail [14, 28–31] formed behind diamond particles during the process of sawing stone with wire saws and circular saws, which leads to the reduction of segment wear and optimize the sawing performance of equipment. Zhang et al. [23, 32, 33] designed a frame sawing machine with an eccentric hinge guide mechanism. The diamond particles under the new type of sawing are easy to form the matrix tail, which improves the holding force and reduces the dropping of the diamond particles. Webb and Jackson [34] observed the wear of segments and the change of sawing forces during sawing, the results indicated that higher sidewall wear may cause the blade to ‘knife edging’ and accelerate radial wear. The sawing experiment on the frame saw with a reciprocating swing mode was conducted Dong et al. [35]. The results demonstrated that reducing the cutting arc and the number of cutting segments can improve the stability of saw blades. Li et al. [36] found that the roughness of the workpiece decreases as the wire speed increases when the speed is low.

The topic of this paper aims at the sawing performance of frame saw with the horizontal reciprocating cutting mode. The average thickness of the cutting chip model was
established and the reasons for the different cutting forces on segments were explained. The mechanism of the segmented wear and the discrepancy of saw kerfs were investigated based on the wear characteristic of the diamond segments and the width of the saw kerf.

2 Experiment procedure

2.1 Sawing equipment

Experiments were conducted on the diamond frame saw with horizontal reciprocating sawing mode, as shown in Fig. 1. Saw blades are installed on the frame and diamond segments are welded at the bottom of the saw blade body.

The equipment is mainly used to saw large-size natural stone into slabs of specified thickness. The sawing movement mainly includes the horizontal reciprocating movement of the saw blade and feed movement of the stone. The horizontal reciprocating movement is realized by the crank connecting rod mechanism and the feed movement is driven by the lifting device. The parameters of sawing are listed in Table 1.

2.2 Sawing tools and workpiece

The experimental tools were saw blades with dimensions of 4100 mm (length) × 3.5 mm (width) × 180 mm (height) and diamond segments with dimensions of 23 mm

| Parameters         | Values |
|--------------------|--------|
| Dominate motor (kw)| 110    |
| Flywheel speed (r/min) | 60    |
| Feed motor (kw)    | 15     |
| Stroke (mm)        | 600    |
| The flow rate of cooling water (L/min) | 10 |
(length) × 4.8 mm (width) × 14 mm (height). Table 2 provides some information on the diamond segment. Two pieces of Brazilian gold granite with different sizes were used as experimental workpieces, in which the sizes of 200 mm (length) × 80 mm (width) × 80 mm (height) were taken to measure the cutting forces, the sizes of 2600 mm (length) × 1500 mm (width) × 1950 mm (height) was adopted to analyze the characteristics of segment wear. The main characteristic parameters of granite are displayed in Table 3.

### 2.3 Sawing tests

The cutting forces ($F_n$, $F_t$, and $F_z$) in three directions were measured by a Kistler dynamometer (Kistler 9257B). The schematic illustration of the cutting forces experiment is displayed in Fig. 2. The height of segments and the width of saw kerfs under different cutting parameters were obtained by a vernier caliper. Each measurement was repeated four times and mean values were calculated. Then the detailed information of segments was observed by a three-dimensional imaging system (VHX-600) and scanning electron microscopy (JSM-6610LV). Besides, the protrusion height of diamond grits was measured through a laser scanning confocal microscope (LSM800), as shown in Fig. 3.

### 3 Results and discussions

#### 3.1 Cutting forces

#### 3.1.1 Characteristics of cutting forces

The forces are measured to verify their effect on the sawing process. Figure 4 illustrates the cutting forces in the stone processing. The forces change periodically; besides, the feed cutting force ($F_n$) and the cutting force ($F_t$) show a tendency of decreasing firstly and then increasing in a single stroke, the minimum value and maximum value are obtained at the midpoint and the reversing point, respectively. More specifically, the cutting force has positive and negative changes in the forward and return strokes.

This is because the horizontal motion and vertical feed motion of sawing machine are independent. The horizontal motion is controlled by the crank linkage mechanism, and the vertical direction is fed continuously by the feed motor. When the horizontal motion reaches two reversing points, the horizontal speed is 0, but the vertical direction is still feeding at a constant speed. Therefore, the cutting force reaches the maximum value at the reversing point, which is greater than the cutting force in stable cutting. Besides, the cutting forces change with the number of diamond segments that are contacting with the stone at the same time. The more the number of diamond segments, the greater the cutting forces. The cutting forces of a segment at different feed speeds are shown in Fig. 4b. $F_n$, $F_t$, and $F_z$ are feed cutting force, cutting force, and lateral force, respectively. It can be observed that the feed cutting forces increase with the feed speed, which is consistent with the research results of many scholars [1–3]. As shown by experiments results, the realistic machining situation could be reflected by a single diamond segment. According to Fig. 4, the cutting forces ($F_n$ and $F_t$) reach 164.124 N and 53.86 N, respectively, when the feed speed reaches 80 mm/h, which indicates that the sawing resistance is the largest.

#### 3.1.2 The establishment of the average chip thickness model

To reveal the relationship between the sawing parameters and the cutting forces, the theoretical model of average chip thickness changing with cutting parameters was established, as shown in Fig. 5.

The cutting chip can be regarded as a pentahedron with a triangular cross-section within a single stroke time (assuming that each diamond particle is cutting from beginning to end). The feed rate (mm) of a segment in a single stroke can be expressed as

$$h_f = \frac{v_f}{120 \times n} \quad (1)$$

where $v_f$ (mm/h) is the feed speed of the stone and $n$ (rpm) is the rotating speed of the flywheel.
Therefore, the largest undeformed volume of cutting chip (mm³) removed in a single stroke time can be represented as

\[ V = \frac{h_f \times l_s \times b}{2} \]  \hspace{1cm} (2)

where \( l_s \) (mm) is the center distance between two diamonds and \( b \) (mm) is the height of the cutting chip based on the bottom surface.

The diamond segment is made by the sintering process, in which particles are distributed on the segment randomly, so the average depth of cut (mm) can be expressed by Eq. (3):

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\[ \text{Fig. 2} \quad \text{The schematic of sawing experiment} \]

\[ \text{Fig. 3} \quad \text{Measurement of the protrusion height} \]
where \( L \) (mm) is the length of stroke. The average depth of cut refers to the vertical downward displacement of diamond segments in a single stroke time, and the average thickness of the cutting chip is the vertical distance between adjacent tracks in a single sawing.

Figure 6 displays the sawing motion of the saw blade in the direction of \( x \) and \( y \), it can be expressed by Eq. (4) and Eq. (5), respectively.

\[
x = \frac{L}{2}(1 - \cos 2\pi nt) \tag{4}
\]

\[
y = \frac{v_f}{3600} t \tag{5}
\]

The functional relationship between \( y \) and \( x \) be calculated by Eq. (6):

\[
y = \frac{v_f}{7200\pi n} \arccos \left(1 - \frac{2x}{L}\right) \tag{6}
\]

Point A is any point except the reversing point; the slope at point A can be expressed as

\[
y' = \frac{v_f}{7200\pi n \sqrt{xL - x^2}} \tag{7}
\]

The angle at point A can be described as

\[
\tan \alpha = y' \tag{8}
\]

\[
\cos \alpha = \sqrt{\frac{xL - x^2}{xL - x^2 + A^2}} \tag{9}
\]
Owing to the value is 1 during sawing except for the reversing point, so $\alpha$ can be ignored.

The average chipping thickness can be described as

$$h_t = \frac{h_d}{\cos \alpha}$$

Therefore, the average thickness of the cutting chip can be written as

$$h_t = \frac{v_f \times l_s}{240 \times n \times L}$$

The average chipping thickness increases with the feed speed and increases with the decrease of the rotating speed. According to previous studies [1–4], the cutting forces increase with the average chipping thickness. Therefore, the cutting forces are increasing as the feed speed becomes higher, which leads to the wear of diamond segments.

3.2 Wear morphology of the diamond segments

3.2.1 The proportion of different particles

The wear morphology of the segments was displayed in Fig. 7. The diamond particles could be divided into six states, fresh, whole, micro-fractured, macro-fractured, blunt, and pulled-out diamond particles. Figure 7a is the image of fresh diamond particles exposed after matrix consumption. Figure 7b is the image of diamond particles with integrity surface and sharp cutting edge, which performs best in the cutting work. Figure 7c is the image of diamond particles with slight cracks or breakage on the surface. Figure 7d shows that the diamond with serious surface damage and large-scale shedding, which lost the ability to saw. Figure 7e shows that the diamond particles are in an unsteady cutting state and the sharp diamond particles are blunt. Figure 7f is the deep pit left after the diamond particles fell off. As illustrated in Fig. 7f, the cracks and fractures were not found around the pits formed by the fallen diamond particles, which indicates that diamond particle shedding is caused by insufficient holding force.

When the rotating speed of the flywheel is maintained at 60 r/min, the proportion of macro-fractured and pulled-out particles on segments at different feed speeds is shown in Fig. 8. The results reveal that the values were more than 1/3, which increased from 29.6% at 60 mm/h to 40% at 80 mm/h because the cutting forces are directly related to the state of diamond particles. The higher the feed speed, the larger the average thickness of the cutting chip, the greater the cutting force as analyzed in Sect. 3.1. Therefore, the phenomenon of macro-fractured and pulled-out particles could be more obvious.

The protrusion height of diamond particle is obtained through the laser scanning confocal microscope. A total of 30 diamond particles are measured and each measurement was repeated three times. Finally, the average protrusion height of 86.3 $\mu$m is obtained after calculating. The results show that the protrusion height of diamond particles is below 100 $\mu$m. The cutting forces become larger during sawing hard stone such as granite, which causes the diamond particles to fall off before performing their cutting function. At the same time, the diamond particles are prone to breakage, resulting in the overwhelming of macro-fractured particles when the mechanical impact load is large, as shown in Fig. 9.

The forces on diamond particles become larger, the diamond particles fall off, and broken macroscopically become more serious as the feed speed increases, so the mean protrusion height of the diamond segments decreases. Ultimately, the diamond segments lose their sawing ability. This is consistent with the analysis in Sect. 3.1, the cutting forces become larger, and the proportion of macro-fractured and pulled-out grits become higher as feed speed gets higher.

3.2.2 The mean wear rate of segment

The mean wear rate of the segment can be defined as the ratio of the difference of the initial height and remaining height of segments to the sawn area of stone. As displayed in Fig. 10, the wear rate of segments increases with the feed speed obviously. The value of wear rate at 80 mm/h reaches 919.19 $\mu$m/m², which is significantly higher than that at 60 mm/h. The cutting depths of diamond particles increase with the increase of the feed speed, which leads to higher cutting forces and a higher proportion of macro-fractured and fall-off diamond particles, thus reducing the wear resistance of the segment.

This phenomenon leads to a decrease in the diamond exposure on the whole segment surface, which results in direct contact between the matrix bond and the stone block, further aggravating the segmented wear and forming a vicious circle.
The width of saw kerf

The width of saw kerfs under the conditions of different feed speeds is also measured to explore the sawing performance of the sawblade in cutting granite, as shown in Fig. 11. It can be found that the width of the saw kerf gradually decreases during sawing, forming a cone that is wide at the top and narrow at the bottom. Besides, the gap of the saw kerf increases with the feed speed in the sawing process.
Based on the existing investigations [37–40], the appearance of the inverted cone sawing kerf can be affected by the two factors. The first factor is the excessive force on the saw blade causing the swing in the saw kerf, resulting in an unstable sawing process, and inconsistent sawing width. Moreover, it can be seen from the broken phenomenon on the top of the stone that the saw blade has deviated from the original movement trajectory, as illustrated in Fig. 12. Another factor is the side wear of the segment, which gradually narrows the segment and reduces the kerf width. When the cutting forces of the sawblade exceed the critical instability forces, the saw blade is prone to lose stability and deviate from the original trajectory. Therefore, the diamond frame saw with the horizontal reciprocating sawing mode is not suitable for cutting granite because of the instability of the sawblade and severe wear of the segments.

3.4 The side wear characteristic of the diamond segments

The side wear characteristic of the diamond segments at different feed speeds is shown in Figs. 13 and 14. Each figure is stitched together from 4 to 8 figures. It displays that more obvious protruding diamond particles are exhibited on the side surface at higher feed speed, which is mainly attributed to the wear rate of the diamond segments.
to the instability of the saw blade, resulting in differences in sharpness on both sides of the segment. The cutting forces increase with the increase of feed speed; thus, the saw blades are more likely to lose stability, which leads to an increase in the forces on the side surface of the diamond segment and the appearance of more diamond particles on the corresponding side. This is consistent with the analysis of the bottom surface of the diamond segments studied in Sect. 3.2. The wear on the bottom and side surfaces of the diamond segments is more obvious as the feed speed increases.
Fig. 13 The side wear characteristic of the diamond segments with the remaining height of 9 mm: a $v_f = 60$ mm/h; b $v_f = 70$ mm/h; c $v_f = 80$ mm/h

Fig. 14 The side wear characteristic of the diamond segments with the remaining height of 4 mm: a $v_f = 60$ mm/h; b $v_f = 70$ mm/h; c $v_f = 80$ mm/h
4 Conclusions

The cutting forces, the segmented wear, and the width of saw kerf were experimented in granite sawing by the diamond frame saw with horizontal reciprocating cutting mode to explore sawing performance. The main conclusions are as follows:

1. The average cutting thickness, sawing resistance, and cutting forces increase with the feed speed, and there are abrupt changes in cutting forces at the reversing point.
2. The proportion of macro-fractured and pulled-out particles is more than 1/3, which increased from 29.6% at 60 mm/h to 40% at 80 mm/h. The mean wear rate of the segments increases with the feed speed, and the mean diamond exposure is low due to the large load during the process of sawing granite.
3. The width of the saw kerf reduced gradually in the sawing process, forming a cone that is wide at the top and narrow at the bottom. Besides, the gap of the saw kerf increases with the feed speed during sawing.
4. The wear of diamond segments increases in two directions (y, z) with the increase of the feed speed, and the prominent phenomenon of grits on the side surface is more obvious.

Author contribution Junjie Wu: investigation and writing; Jinheng Zhang: review and editing; Heng Zhang: advice and guidance; Peiyu Dong: model improvement; Congsen Ouyang: picture processing; Kaida Wang: review.

Funding This work was funded by the Provincial Key R&D Program of Shandong Province, China [NO.2019GGX104022], Scientific and Technological Innovation Project of Rizhao [NO.2019CXZX1109], and Scientific and Technological Innovation Project of Rizhao [NO.2020CXZX1201]. The authors thank Rizhao Hein Saw Co., Ltd. for supplying the diamond frame saw and experimental sites.

Availability of data and material The data and material during the study are listed in this paper.

Declarations

Ethics approval Not applicable.

Consent to participate Yes.

Consent for publication Yes.

Conflict of interest The authors declare no competing interests.

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