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Research Article

Investigations on the Wear Rate of Sintering Diamond Core Bit during the Hole Drilling Process of Al_2O_3 Bulletproof Ceramics

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Bulletproof ceramics are usually hard and brittle with high elastic modulus, high compressive strength, and low tensile strength. While machining bulletproof ceramics, severe tool wear makes it difficult to obtain desired machining quality and efficiency, especially in hole drilling. In this work, an intensive experimental study on the overall wear rate of the sintering diamond thin-wall core bit during the hole drilling of Al_2O_3 bulletproof ceramics (99 wt.%) has been carried out. The quality loss of the bit after each hole drilled was selected for representing the overall wear rate of the bit. Based on experimental data, the influences of the main bit performance and machining process parameters on the overall wear rate of the bit have been analyzed. According to the results discussed, under the test conditions, finer diamond grit, higher diamond concentration, lower number of water gaps, thinner wall thickness, or lower bit load all can decrease the wear rate of the bit. However, within a certain range, the spindle speed has little influence on the overall wear resistance of the bit, but when the spindle speed increases, the machining efficiency can be significantly improved. The results obtained in this work can offer a valuable reference for the use of sintering diamond thin-wall core bits in the hole drilling of bulletproof ceramics.

1. Introduction

Engineering ceramics used in the field of armor protection (bulletproof ceramics) are usually hard and brittle with a very high elastic modulus and have high compressive strength and low tensile strength. During machining engineering ceramics, which are typical difficult-to-machine materials, severe tool wear makes it difficult to guarantee the machining quality and efficiency, especially in the hole machining. This greatly limits the widespread application and popularization in the field of armor protection.

At present, special processing technologies are usually adopted for the machining of hard and brittle materials such as engineering ceramics, including laser processing [1, 2], electrical discharge machining [3, 4], ultrasonic machining [5, 6], and so on. Bharatish et al. [1] performed CO_2 laser drilling tests of 2 mm-thick Al_2O_3 ceramic plates to examine the effects of laser parameters such as pulse frequency, laser power, scanning speed, and hole diameter on entrance circularity, exit circularity, heat affected zone, and taper. Rihakova and Chmelickova [2] made a review about the laser micromachining of glass, silicon, and ceramics. Interaction of these materials with laser radiation and the mechanisms of laser micromachining of materials were provided. In the study by Munz et al. [3], electrically conductive ceramic ZTA-TiC composites were machined by EDM (electrical discharge machining) drilling with variation of pulse shape, discharge current, discharge time, and flushing conditions. Yadav et al. [4] investigated the effects of varied voltage, electrolyte concentration, wire velocity, pulse on-time, and pulse off-time for the EDM of alumina epoxy nanocomposite. Guo et al. [5] designed a novel ultrasonic vibration apparatus and performed the experimental investigation of ultrasonic vibration-assisted grinding of SiC microstructures.

However, special processing technologies are mainly suitable for machining of microholes or microstructures, when it turns to larger holes of about ten mm or even tens of millimeters in diameter, the machining efficiency is very low. When machining a relatively large hole, it is very difficult to drill engineering ceramics with solid bits; therefore, diamond core bits are commonly used [7–11]. Using thin-wall impregnated diamond bits, Zheng et al. [7, 8] performed drilling trials in the ceramics/GFRP/aluminum alloy composite armor formed with 8 mm-thick Al_2O_3 engineering ceramics and only 1.5 mm-thick GFRP and aluminum alloy on each side [7] and the ceramics/KFRP double-plate composite armor formed with 6 mm thick KFRP backboard and 7 mm thick Al_2O_3 ceramic faceplate [8]. Bit parameters, feeding mode, compressive prestress process equipment, drilling efficiency, hole quality, and machining mechanism have been investigated experimentally. Gao and Yuan [9] carried out a comprehensive experimental study on hole drilling of Al_2O_3 armor ceramics by using impregnated diamond bits. The results showed that through selecting the reasonable drill parameters (including matrix composition, diamond type, grain size, diamond concentration, number of slots and wall thickness) and technological parameters (such as axial force and spindle speed), higher efficiency and surface quality can be obtained. Tan et al. [10] designed a new composite-impregnated diamond bit to solve the slipping problem and conducted laboratory drilling test in granite and field drilling application in crystal tuff. Zhang et al. [11] carried out a comparative study on core drilling of silicon carbide and alumina engineering ceramics with monolayer brazed diamond bit. The effect of coolant type and concentration on drilling torque and drilling efficiency and the morphologies of machined surface of ceramics were investigated.

The above analysis indicates that, for large holes machining of engineering ceramics, a higher machining efficiency and better machining quality can be achieved through the optimization of processing parameters and bit performance parameters. Thus, core drilling with diamond bit is an efficient method for machining of holes in engineering ceramics. However, few studies have been reported about the tool wear during the machining of engineering ceramics when employing diamond core bits. Noticeably, Zhang et al. [11] also examined the morphologies of the wear of diamond grains of monolayer brazed diamond bit and found that the wear of brazed diamond grains for drilling of silicon carbide is much severer than that of alumina.

According to the existing literature, investigations on the wear of diamond tools during the machining of engineering ceramics are mainly focused on the abrasive machining of diamond grinding wheels and diamond burs. Kizaki et al. [12] proposed the laser-assisted machining of zirconia ceramics using diamond burs. The results revealed that the grinding force and the tool damage could be reduced in the assisted processes. In the study by Shen et al. [13], the alumina ceramics were ground with and without the ultrasonic vibration-assisted grinding to investigate the wear characteristics of the diamond wheel. The changes of the diamond wheel surface topography were captured during the grinding process. Zeng et al. [14], Liang et al. [15], and Ding et al. [16] also investigated the wear behaviors of diamond grinding wheels during the vibration-assisted grinding process of engineering ceramics in order to improve the machining quality and efficiency and found that the ultrasonic vibration caused greater wear but also improved the self-sharpening property of the diamond wheel. do Nascimento et al. [17] tested the viability of minimum quantity lubrication (with and without water) in grinding of advanced ceramics using a hybrid-bonded diamond wheel. The results showed that the minimum quantity lubrication with water (1 : 1) could reduce wheel wear greatly.

In this study, a typical high-purity alumina bulletproof ceramics (99 wt.% Al_2O_3) was selected as a machining object. Taking the drill quality variation measured as the indicator for reflecting the overall wear degree of the drill, a systematical experimental investigation on the wear rate of the sintering diamond thin-wall core drill has been conducted. The influences of the main bit performance and machining process parameters on the overall wear rate of the bit have been analyzed. The results obtained in the present paper can offer a valuable reference regarding the use of sintering diamond thin-wall core bits to machine bulletproof ceramics.

2. Experimental Procedure

2.1. Sintering Diamond Core Bit. According to the experimental research on the ceramic composite components [7] and double-plate composite components [8], and by combining with the machining features of the bulletproof ceramics, the sintering diamond core bit used in this study is illustrated as Figure 1. The diamond bit is mainly composed of a diamond layer (work layer), a transition layer, basal body, a narrow slot, several water gaps, and a drill shank (clamping handle). The basal body material was made from $45^{\#}$ seamless steel pipe, the diamond grade was SMD_{35}, and the copper-based matrix was fabricated through hot pressing sintering of the metallic binders with volume fractions of 48% Cu, 30% Co, 6% Ni, 5% WC, 5% Ti, 4% Sn, and 2% Cr. The sintering temperature was 900°C, the heat preservation time was 2 min, and the sintering pressure was 20 MPa [7, 8].

2.2. Experimental Set-Up. In order to reflect the overall wear loss variation of the diamond bit accurately, the bit was taken down after every hole was drilled on the bulletproof ceramics and then was washed cleanly and dried for weighing with a precise analytical balance. The overall wear rate of the bit was represented by the quality loss of the bit after each hole was drilled, which reflected the whole wear loss of the diamond grains and the matrix binding agent of the bit. When the drilling operation became significantly difficult or the bit sintering body broke up considerably, the normal drilling operation could not be continued and the bit should be scrapped.

The test was conducted on a ZXL-20 vertical drilling-milling machine (with a spindle power of 750 W) equipped with water cooling device. A constant pressure feed mode

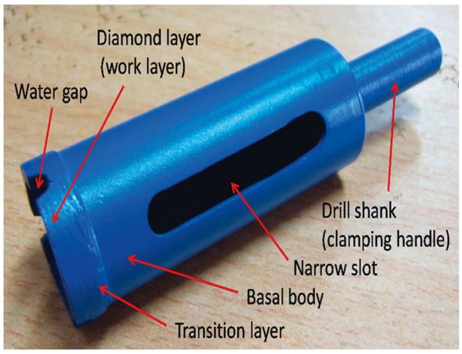

Figure 1: The sintering diamond core bit.

was adopted. The bulletproof ceramics used was a hexagonal high-purity alumina engineering ceramic brick (99 wt.% Al_2O_3) with a thickness of 10 mm. One Al_2O_3 bulletproof ceramic brick drilled is presented in Figure 2. The outer diameter of the bit was Φ 24 mm, and the work layer height was basically the same that of the water gaps, or even slightly smaller. The TG-328B precise analytical balance (as presented in Figure 3) was used for weighing, the reading precision of which was 0.001 g.

With the given matrix formula and diamond grade, the grit size, grit concentration, number of water gaps at the crown, and bit wall thickness are the main bit performance parameters which can affect the wear conditions of the tools. Under the constant pressure feed mode, the bit load and the spindle speed are two important process parameters that affect the wear conditions of the bit. According to the previous experimental studies on the Al_2O_3 ceramic composite armors [7, 8], in the wear test, the performance parameters of the bit and the machining technological parameters have been determined, as listed in Table 1, along with the number of holes that each bit have accomplished until scrapped.

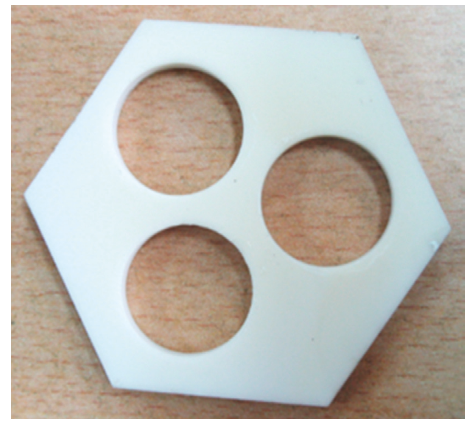

Figure 2: Al_2O_3 bulletproof ceramic brick drilled.

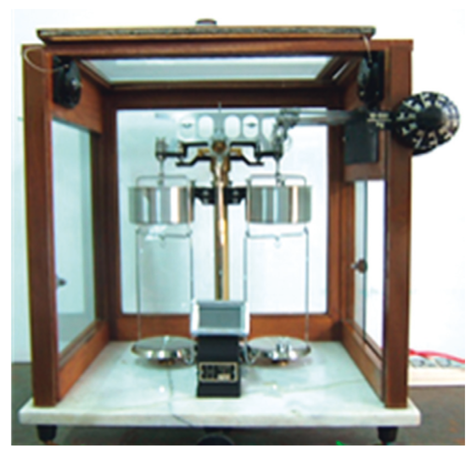

Figure 3: The TG-328B analytical balance.

3. Results and Discussion

3.1. Influence of Bit Performance Parameters on Wear Rate

3.1.1. Diamond Grit Size. Figure 4 shows the comparison results of the bit overall wear rate of the bit when the diamond grit size is 35/40 mesh (Test 1) and 50/60 mesh (Test 2), respectively. When the grit size is 35/40 mesh, the diamond layer is completely exhausted after machining the 23rd hole, and accordingly, the bit begins to skid. This means that the work layer has been fully utilized. When the grit size is 50/60 mesh, the bit begins to skid when drilling the 13th hole (not drilled through), and the work layer has not been fully taken use of.

As can be seen from Figure 4, when other conditions are kept constant, the decrease of the grit size can reduce the overall wear rate of the bit, thus enhancing the wear resistance of the drill. However, it is also found that the service life of the bit has not been extended accordingly. When the grit concentration is constant, the increase of the grit size can decrease the number of grinding grains on the diamond bit crown. Therefore, under the constant pressure feed mode, the cutting depth of a single diamond grit increases, making the ceramic material easy to be fractured and cracked. Meanwhile, more large-sized ceramic abrasive debris is produced, which has a more severe wear effect on the bit.

In addition, the cutting load on a single diamond grit increases, which makes the diamond easy to break or fall off. Thus, new diamond grits can be constantly exposed to the working surface, and the performance of diamond bit can be fully taken use of. When the grit size becomes smaller, diamond grits exposed on the lip surface of the drill is increased, the cutting depth of a single diamond grit decreases (under a constant drilling load), the size of ceramic abrasive debris becomes smaller, and the wear of bit also becomes slighter; meanwhile, the cutting load on a single diamond grit decreases, and the diamond is easy to be worn into a planar shape, which results in the occurrence of the skidding phenomenon [7], such as the bit in Test 2. Therefore, a finer diamond grit does not always lead to a longer bit life, and it seems that an optimal diamond grit exists under certain machining conditions.

3.1.2. Diamond Concentration. Figure 5 shows the comparison results of the overall wear rate of the diamond bit when the diamond concentration is 75% (Test 1) and 125% (Test 3), respectively. When the diamond concentration is

Table 1: Test conditions.

Test no.	Bit performance parameters Grit size (mesh)	Concentration (%)	Number of water gaps	Wall thickness (mm)	Technological parameters Bit load (N)	Spindle speed (rpm)	Number of machined holes
1	35/40	75	3	2	352	3200	23
2	50/60	75	3	2	352	3200	13
3	35/40	125	3	2	352	3200	26
4	35/40	75	2	2.5	278	3200	33
5	35/40	75	4	2.5	278	3200	21
6	45/50	125	4	2	390	3200	15
7	45/50	125	4	2.5	390	3200	9
8	35/40	75	3	1.5	352	3200	9
9	45/50	125	4	2.5	278	3200	23
10	35/40	75	3	2	352	1750	21

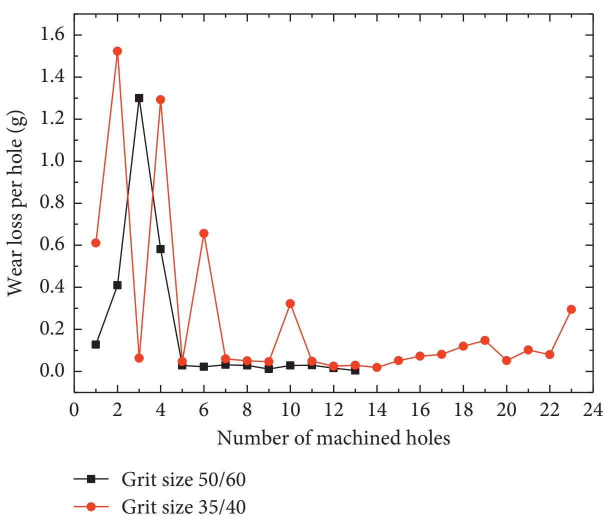

Figure 4: Wear rates of the bit under different diamond grits.

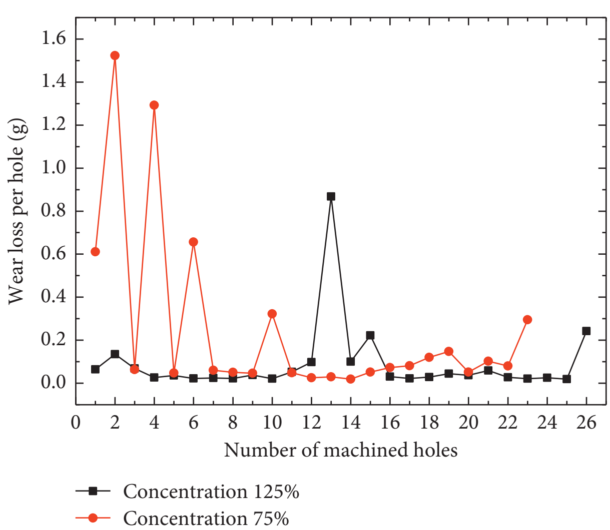

Figure 5: Wear rates of the bit under different diamond concentrations.

125%, massive breakup of the sintering body occurs after drilling through the 26th hole, and the work layer has not been fully taken use of.

Further, it can be seen from Figure 5 that when the concentration increases, the wear rate of the diamond bit can obviously decrease. When the concentration increases, the density of diamond grits on the bit crown surface becomes larger, and the bare area of the matrix reduces; thus, the wear resistance of the bit matrix increases. Under a constant pressure feed, the cutting depth of a single diamond reduces and the particle size of ceramic abrasive debris becomes smaller, the wear effect of the ceramic abrasive debris on the bit thus reduces and the wear resistance of the bit increases. At the same time, the cutting load of a single diamond grit is reduced, and more diamond grits are prone to be worn and exhausted. When the wear of the diamond grits proceeds to a certain level, a large number of the exposed diamond grits are ground and polished, i.e., the occurrence of skidding phenomenon. In addition, the increase of diamond concentration decreases the bond strength of the matrix and probably induces the breakup of the sintering body during the drilling process, thus leading to the bit being scrapped prematurely, such as the bit in Test 3.

When the concentration is relatively low, the cutting load acting on a single diamond grit becomes higher and the cutting and breaking of the ceramics becomes easier. Accordingly, the diamond grits on the bit crown are more prone to fragmentation wear, and the abrasion wear of diamond grits reduces. In this way, the cutting ability of the bit can be preserved. However, if the concentration is too low, the massive fragmentation of diamond grits will increase rapidly, which may cause severe wear and premature scrap of the bit. However, if the concentration is too high, the holding strength of the matrix binding agent to the diamond grits is not high enough and the diamonds are prone to fall off prematurely during the machining process, where the wear resistance of the bit is reduced.

3.1.3. Number of Water Gaps on the Crown. Figure 6 shows the comparison results of the overall wear rate of the diamond bit when the number of water gaps on the crown of bit matrix is 2 (Test 4) and 4 (Test 5), respectively. When the number of water gaps is 2, the bit begins to skid when drilling the 33rd hole (not drilled through), and the work layer is not completely used. When the number of water gaps

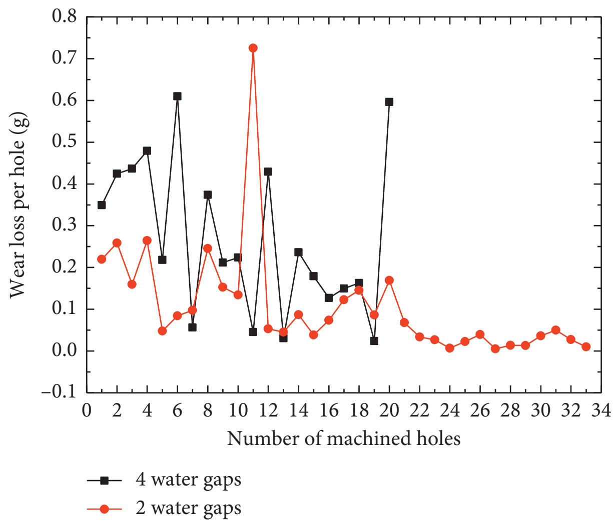

Figure 6: Wear rates of the bit under different number of water gaps.

is 4, at the beginning of drilling the 21st hole, the noise sharply increased, the bit jittered considerably, and the clamping shank twisted off quickly. It can be found that the water gaps have been ground to disappear, and that no diamond grits remain on the crown, namely, the diamond layer has been completely exhausted. At this moment, the bit work layer has been also fully used.

According to Figure 6, it can be found that, on the whole, the bit wear resistance is stronger when a smaller number of water gaps is employed. With the increase of the number of water gaps on the crown, the surface area of the work layer on the bit crown is reduced, and the number of exposed diamond grits is also reduced. Under the constant pressure feed mode, the cutting load of a single diamond grit increases, and the depth of the diamond cutting into the ceramic workpiece increases as well, the ceramic materials are thus more likely to be broken into large pieces. In addition, the particle size of ceramic abrasive debris being relatively large, it enhances the wear effect on the bit and leads to a poor wear resistance of the bit, as presented in Test 5. Meanwhile, a greater number of water gaps increases the frequencies of mechanical and thermal shocks. Frequent impacts decrease the binding strength of the diamond grits and the matrix, and accelerate the fall-off rate of the diamond grits; moreover, they are likely to cause massive fragmentation wear of diamond grits, thus reducing the wear resistance of the bit.

In addition, when the number of water gaps increases, the difference between the cutting loads on the diamonds at the inner and outer cutting circular lines increases, which further aggravates the uneven wear of the bit crown and degrades the wear resistance of the bit. In contrast, when there are fewer water gaps, the work layer surface area of the bit crown increases and the exposed diamond grits on the crown increases; the cutting load of a single diamond grit is thus reduced, and the proportion of diamond abrasion wear is increased. This probably leads to the skidding phenomenon, for example, the bit in Test 4. Therefore, the number of water gaps should be determined according to specific processing conditions. According to the machining tests on bulletproof ceramics carried out in this investigation, the number of water gaps should be set to 2-3 (when the bit diameter is Φ 24 mm).

3.1.4. Bit Wall Thickness. Figure 7 shows the comparison results of the overall wear rate of the diamond bit when the wall thickness of the bit is 2 mm (Test 6) and 2.5 mm (Test 7), respectively. When the wall thickness of the bit is 2 mm, after machining the 15th hole, massive breakup of the diamond layer occurs, and the bit is scrapped. This means that the bit work layer has not been fully used. When the wall thickness is 2.5 mm, the clamping drill shank twists off when machining to the 9th hole (not drilled through). It can be found that no water gaps and no diamond grits remain on the crown, indicating that the diamond layer has been completely exhausted.

As can be seen in Figure 7, when the wall thickness increases, the wear rate of the bit increases obviously as well. This is because when the wall thickness increases, the surface area of the work layer of the bit crown also increases and accordingly the wear loss increases. However, it is also found that when the wall thickness increases, the service life of the bit is not extended accordingly; on the contrary, it is the bit with thinner wall thickness that shows a longer service life. It is observed that when the bit load is 390 N, bits with larger wall thickness show a very obvious inner trumpet-shaped wear shape on the crown. This uneven crown wear decreases the matrix strength and wear resistance of the bit. Further, the impact load per unit area on the crown matrix increases dramatically, and thus, the wear rate of the bit remarkably increases combined with screeching noise and bit bouncing, which decreases the service life of the bit tremendously. In contrast, when the wall thickness is thinner, although the volume of the diamond layer is reduced, the wear rate of the bit is relatively stable and the fluctuation is not very high, resulting in an improved service life of the bit.

On the whole, with the increase of wall thickness, the difference between the feed load and cutting load of the diamond at the inner and outer cutting circular lines is increased, so the uneven wear of the bit crown becomes more severe, which leads to a faster bit wear. In addition, when the wall thickness is relatively thin, the strength of the bit sintering body is reduced, so that cracking and even breakup of the diamond layer are easy to occur during machining, such as the bit in Test 6.

It is noticed that the bits in Test 3 (bit load is 352 N, and wall thickness is 2 mm) and Test 8 (bit load is 352 N, and wall thickness is 1.5 mm) are also scrapped prematurely because of the massive breakup of the sintering body. Therefore, the appropriate wall thickness and bit pressure has a crucial impact on the normal use of the bit. According to the machining tests of the bulletproof ceramics, the appropriate wall thickness should not be more than 2.5 mm and not less than 2 mm (when the bit diameter is Φ 24 mm). Too thick a wall thickness would reduce the service life of the bit due to the seriously uneven wear of the crown. Too thin a wall

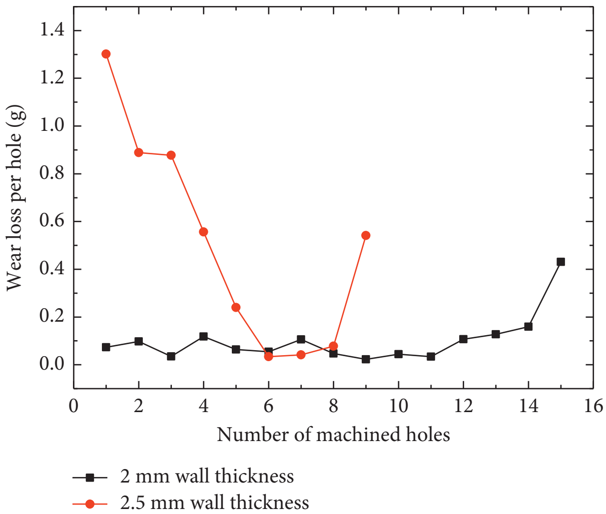

Figure 7: Wear rates of the bit under different wall thicknesses.

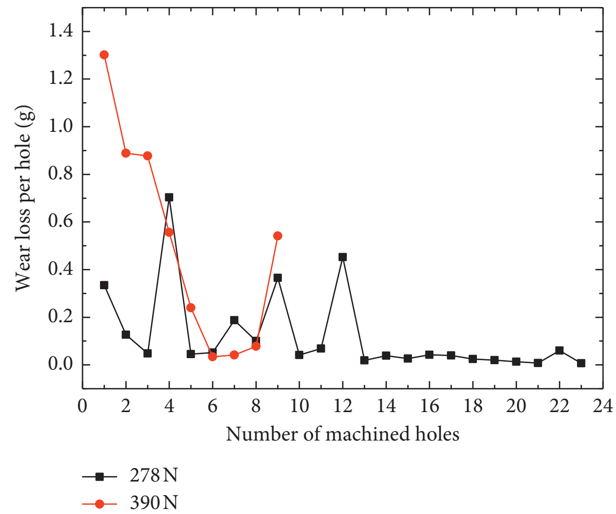

Figure 8: Wear rates of the bit under different bit loads.

thickness would lead to a poor strength and rigidity of the bit sintering body, which would result in the breakup of the work layer during machining process, finally causing the scrap of the bit prematurely. As a result, the wall thickness should match the bit load to obtain a longer bit service life.

3.2. Influences of Machining Technological Parameters on Wear Rate

3.2.1. Bit Load. Figure 8 shows the comparison results of the overall wear rate of the diamond bit when the bit load is 278 N (Test 9) and 390 N (Test 7), respectively. When the bit load is 278 N, after 23 holes are machined, the machining is not continued because this batch of ceramic bricks has been completely used out. At this moment, the depth of water gaps was 1.8 mm, and there were no cracks in the diamond layer. The bit preserved its good drilling performance and could still be used for further machining operations.

From Figure 8, it can be seen that reducing the bit load can greatly decrease the wear rate of the diamond bit. When the bit load is reduced, the cutting load applied on the diamond grits on the crown decreases and the impact effect to which the diamond grits are subjected is also reduced; thus, the massive fragmentation and fall-off of the diamond grits is reduced; at the same time, the depth of a single diamond grit cutting into the ceramics is decreased, and the particle size and the total amount of ceramic abrasive debris are both reduced, the wear effects of the abrasive debris on the matrix binder and the grits are therefore alleviated. Especially, the impact wear of the coarse ceramic hard debris particles on the diamond grits and the matrix are greatly reduced. The repeated impacts of these coarse ceramic hard debris particles can not only accelerate the fall-off of the diamond grits on the crown but also rapidly scratch and wear the matrix, which results in an extremely violent wear effect on the bit. Therefore, the overall wear rate of the bit can be greatly decreased by decreasing the bit load. Compared with the bit load of 390 N, under the bit load of 278 N, the diamond bit can maintain stable wear for longer time, and consequently, the bit life can be extended considerably.

It can be observed that when the wall thickness is 2.5 mm (Tests 4, 5, 7, and 9), an inner trumpet-shaped wear of different degrees appears on the matrix crown during the machining process [7]. Especially when the bit load is relatively high (for example, the bit load is 390 N in Test 7), very obvious inner trumpet-shaped wear is found on the bit crown. This uneven wear of crown accelerates the overall bit wear rate greatly and considerably decreases the service life of the bit. In comparison, when the bit load is reduced to 278 N (Tests 4, 5, and 9), the uneven inner trumpet-shaped wear of the crown is greatly alleviated, and the service life of the bit is also extended significantly.

Therefore, the increase of wall thickness does not always enhance the wear resistance or extend the service life of the bit; the key is to match the wall thickness with the bit load. Only a reasonable bit load can make full use of the bit work layer and thereby achieve a longer service life.

3.2.2. Spindle Speed. Figure 9 shows the comparison results of the overall wear rate of the diamond bit when the spindle speed is 1750 rpm (Test 10) and 3200 rpm (Test 1), respectively. When the spindle speed is 1750 rpm, the diamond layer is completely exhausted after machining the 21st hole, and the bit work layer has been fully used.

It can be seen from Figure 9 that under test conditions, the change of the spindle speed has little effect on the overall wear resistance and service life of the bit, i.e., the average wear rate of the bit is basically kept constant. However, at the relatively high spindle speed, the wear rate of the bit exhibits a very large fluctuation, while at the relatively low spindle speed, the wear rate of the bit is relatively smooth. Compared with the spindle speed of 1750 rpm, when the spindle speed is increased to 3200 rpm, the average machining time per hole is about half of the time under the former speed. Hence, after increasing the spindle speed, the machining efficiency of the bit can be enhanced substantially. This is because

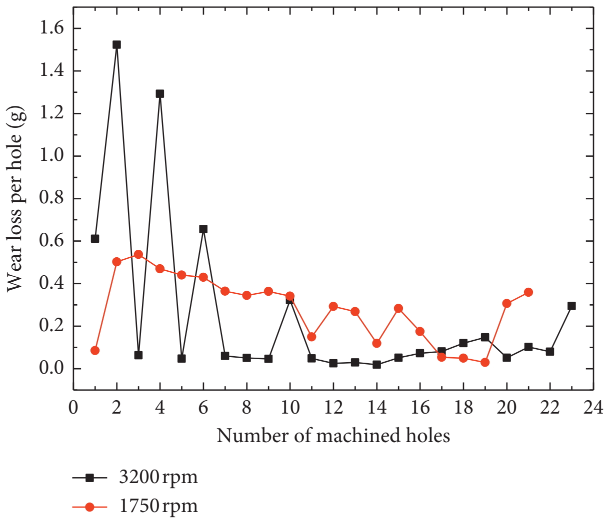

Figure 9: Wear rates of the bit under different spindle speeds.

when the speed is relatively low, the vibration of the bit during the machining process is moderate, which reduces the dramatic collision wear between the diamond grits and matrix and the ceramic materials. As a result, the massive fragmentation and fall-off phenomena of the diamond grits are alleviated, and the wear rate of the matrix is relatively stable. Hence, the wear rate of the bit is relatively smooth at low speeds. However, it should be noticed that the decrease of spindle speed will directly lead to the decrease of the linear velocity of the bit, which means that smaller volume of ceramic material can be cut by the single diamond grit per unit time. Therefore, the machining efficiency is decreased.

In addition, according to the study [18], the decrease of the spindle speed leads to a decrease in the axial cutting force acting on the diamond bit and accordingly the grinding force of a single diamond grit decreases. At this moment, the wear rate of the grits decreases; however, due to the decrease of the spindle speed, the machining time of per hole is significantly extended, which results in larger machining and wear times. Thus, the wear of grits during the entire hole machining process is not reduced. It can therefore be concluded that the increase of spindle speed within a certain range will not lower the overall wear resistance or accelerate the average wear rate of the bit significantly, but can increase the drilling rate substantially.

3.3. Relationship between Bit Wear Rate and Cumulative Drilling Depth. The cumulative drilling depth of the bit can be represented by the total number of machined holes. Hence, Figures 4–9 also reflect the relationship between the overall wear rate of the bit and the cumulative drilling depth. It can be found from Figures 4–9 that the wear rate of the bit shows an approximately periodic variation with the accumulated drilling depth, namely, the abrasion loss per hole varies from low (high) to high (low) and then from high (low) to low (high). Although the periodic trend is not very regular, the special wear characteristic of the bit can be qualitatively described.

This special wear characteristic of the sintering diamond bit is closely related to the periodical layer-changing characteristic of the diamond grits on the crown surface of the impregnated diamond tools. Since the diamond grits are randomly distributed in the matrix, with the continuous wear of the matrix body, the diamond grits are exposed layer by layer and act as microcutting edges to cut the ceramic material and are worn gradually, broken, and finally fall off, namely, continuously working in the form of periodical layer-changing [7]. When the exposed diamond grits on the crown of the matrix reach a certain amount and the diamond grits are mostly at the abrasion wear stage, the abrasion loss of the bit is small, and the wear process is relatively stable. When the diamond grits are at the massive fragmentation or fall-off stage, new diamond grits are continuously exposed, and the wear loss of the bit is high. When the diamond grits on the crown are dominated by the microfragmentation wear, the wear loss of the bit is between the above-mentioned two conditions. Hence, in Figures 4–9, the relationship between the overall wear rate of the bit and the cumulative drilling depth is reflected as the continuous variation of the wear rate with the number of cumulative machined holes. This working process of the diamond bit goes round and round until the diamond bit is scrapped by the skidding of the bit, the breakup of the sintering body, or the depletion of the diamond layer.

In general, if the wear loss of the bit after machining a certain hole is large, the bit should be in the layer-changing process of the diamond grits on the crown surface when the hole is being machined, whereas when the wear loss of the bit after machining a certain hole is small, the bit should be at the abrasion wear stage or microfragmentation wear stage. Thus, during the hole machining process, the bit is sometimes at the abrasion wear stage, sometimes at the microfragmentation stage, sometimes at the massive fragmentation or fall-off stage, and sometimes in the layer-changing process of the diamond grits on the crown surface. Hence, in the machining process of each hole, the state of the diamond grits on the crown surface is different, which leads to differences in the wear loss after machining different holes. Since the wear loss after machining each hole is used to represent the overall wear rate of the bit, the wear rate curve of the bit sometimes does not cover a complete cycle, such as in Test 7 (Figure 8). It should be noticed that this phenomenon does not mean that there is no periodical variation for the bit wear rate in the hole machining process.

4. Conclusions

In this work, an intensive experimental study on the wear rate of the sintering diamond thin-wall core bit during drilling Al_2O_3 bulletproof ceramics (99 wt.%) has been conducted. The influences of the main bit performance and machining process parameters on the overall wear rate of the bit have been analyzed. According to the experimental results, the main conclusions can be summarized as the following:

(1) Under the test conditions, finer diamond grit, higher diamond concentration, lower number of water gaps, thinner wall thickness, or lower bit load all can decrease the wear rate of the bit.

(2) When the diamond grits turns finer, the diamond concentration turns higher, or the number of water gaps is lowered, the bit can skid easily, whereas thinner wall thickness and higher diamond concentration can make the diamond layer to crack easily or even break up. The increase in wall thickness does not always increase the wear resistance or extend the service life of the bit, and the key is to ensure the matching of bit load and wall thickness.

(3) From the perspective of wear resistance, the number of water gaps should be 2-3, and the wall thickness should be kept between 2 and 2.5 mm (when the bit diameter is Φ 24 mm).

(4) Within a certain range, the spindle speed has little influence on the overall wear resistance of the bit, but when the spindle speed increases, the machining efficiency can be significantly improved.

(5) The wear rate of the bit shows an approximately periodical variation with the cumulative drilling depth. This is closely related to the periodical layer-changing characteristic of the diamond grains on the working surface of the impregnated diamond tools.

Data Availability

The wear rate data of the sintering diamond core bit under different bit performance and machining process parameters involved in this paper can be found in the figures drawn with Origin software. The data can be sent by e-mail.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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