Experimental Study on Peck Drilling of Micro-holes in Fully Sintered Zirconia Ceramics Using Diamond-Coated Drill Bits

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Abstract: Zirconia (ZrO_2) ceramic material has been widely applied to various fields due to its unique properties of high strength, high hardness, and excessive temperature resistance. However, the high-quality micro-hole machining of zirconia ceramic material remains a significant challenge at present. In this study, experiments on peck drilling of ∅0.2 mm and ∅0.5 mm micro-holes in zirconia ceramics using diamond-coated drills are conducted. The characteristics of the force signal during the drilling process, the influence of drilling parameters on the drilling force and the chipping size at the hole exit, and features of the tool wear stages of the diamond coated drill are analyzed. Experimental results suggest that when machining micro-holes in zirconia ceramics, there is a positive correlation between the axial force and the size of the chipping at the exit. The axial force increases with the increase of the feed rate and the step distance, and it shows a trend of first increasing and next decreasing with the increase of the spindle speed. The wear of the drill bit has a significant impact on the quality of the hole exit. It is found that with the continuous drilling of seven holes, the axial force increases by 144.2%, and the size of edge chipping at the exit increases from about 20 μm to more than 130 μm. This study can provide some valuable references for improving the micro-hole processing quality of material.

Key words: zirconia ceramics; diamond-coated; peck drilling; chipping; tool wear

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0 Introduction

Zirconia (ZrO_2) ceramics are commonly known as "hard and brittle" materials due to their exceptional properties, such as high hardness, heat resistance and chemical stability, and low thermal conductivity. They have been widely used in various industries as green materials, such as national defense, chemical industry, metallurgy, electronics, machinery, aerospace, and biomedicine[1-2]. During the sintering process of zirconia ceramics, the grain size undergoes continuous changes, accompanied by corresponding variations in physical and mechanical properties. This constitutes a complex integrated process involving mass transport and geometric evolution. Tetragonal-phase zirconia ceramics exhibit optimal mechanical properties and chemical stability, yet they are difficult to maintain in a stable state at room temperature. Therefore, Y_2O_3 is added as a stabilizer during sintering to obtain high-performance tetragonal-phase ceramic materials. Different addition amounts make the material exhibit different hardness and toughness[3]. Ji et al.[4] investigated the evolution of material removal mechanisms in 3Y-TZP ceramics during sintering. Their study revealed that a sintering temperature of 1 100 ℃ serves as a critical transition point for the material removal mechanism in 3Y-TZP. When sintered above 1 100 ℃, the removal mechanism shifts to a

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typical ductile-brittle transition behavior.

With the development of modern equipment in the direction of miniaturization and integration, the machining requirements for micro holes and slots have increased from various precision parts to common commercial devices. However, the hole processing for ZrO_2 ceramics often results in significant tool wear and compromises the quality of holes.

Generally, it is difficult to reserve holes that meet precision and dimension requirements after ceramic sintering, and subsequent processing is often required. However, engineering ceramics is a typical material that is difficult to machine[5]. The material itself has high brittleness and poor toughness, so it is easy to produce microcracks chipped edges, and other defects in the drilling process. When the chipped edges are generated, the subsequent processes are generally required to eliminate them. Sometimes, the workpiece is directly scrapped due to excessively chipped edges, increasing the processing cost of ceramic parts[6]. Therefore, it is of great significance to find a process method that can reduce the edge chipping at the outlet of ceramic materials to improve the processing quality of parts and reduce the cost.

At present, laser machining, micro-electric spark machining, micro ultrasonic machining, and other commonly used special machining technologies are applied to the machining of micro-holes of hard-brittle materials such as engineering ceramics. Bharatish et al.[7] studied laser drilling of alumina ceramics, the influence of laser parameters on the hole entrance and outlet, and the influence of residual thermal stress on the material. Chen et al.[8] studied the effect of laser parameters on micropore processing of alumina ceramic substrates by experiment and simulation. The results show that larger laser power and pulse number can produce a larger aperture and hole depth, and the hole wall taper is related to the pulse duration. Rashid et al.[9] machined micropores on aluminum nitride ceramics by micro-electric discharge machining technology. To study the effect of process parameters, gap voltage, and electrode rotational speed on the material removal rate and the hardness of the re-cast layer. Banu et al.[10] used a tool electrode with a diameter of 0.8 mm to perform micro-discharge machining on the zirconia ceramic, obtained the best process parameters and established an empirical model for the hardness of the recast layer. Lalchhuanvela et al.[11] conducted an ultrasonic drilling test on alumina ceramic and studied the influence of abrasive grain size, feed speed, ultrasonic power, and other parameters on hole-forming morphology and size. Liu et al.[12] used a CVD coated bit with a diameter of 0.5 mm to drill rotary ultrasonic holes for alumina ceramics, studied the influence of machining parameters on tool wear and hole outlet damage, and put forward an optimization scheme on this basis. Li et al.[13] established a simulation model for machining 3Y-TZP ceramics using ultrasonic elliptical vibration cutting and conducted experimental validation to investigate the material removal characteristics and crack propagation mechanisms during the machining process. The study reveals that when the ultrasonic speed ratio falls below the critical value of 0.128, a larger plastic deformation zone can be achieved during processing.

Most micro-drilling research focuses on metal materials and composite materials. It is found that when machining small and deep holes, it is not easy to remove the chips generated in the machining process, and even if coolant is used, the cooling effect of the machining area is difficult to achieve, which is easy to cause serious tool wear and processing hardening and other problems[14].

In order to better study the micro-drilling process in high-precision micro-diameter machining, relevant scholars have established relevant models for the machining process, which can effectively monitor or predict the machining situation. Anand et al.[15] established a micro-drilling cutting force model and proved its effectiveness through tests. Patra et al.[16] established an artificial neural network (ANN) model to predict the number of boreholes by combining machining parameters such as cutting force and feed rate in mechanical drilling.

Machining high-hardness materials such as zirconia ceramics imposes stringent requirements on cutting tools, with tool materials typically limited to superhard substances like diamond and CBN. Xu et al.[17-18] conducted milling experiments on 3Y-TZP ceramics using both PCD and PCBN tools. The results demonstrated that PCD tools exhibited superior performance in terms of milling forces, cutting temperature, and surface quality. And further study found that feed per tooth significantly influenced surface quality. Additionally, PCD tools displayed higher wear resistance at lower cutting speeds. Liu et al.[19] evaluated the performance of 2-mm-diameter carbide tools, diamond-coated tools, and micro-sintered tools in drilling zirconia ceramic plates. A detailed analysis of tool wear mechanisms revealed that diamond-coated tools reduced axial forces by approximately 60% compared to carbide tools, achieving significantly better machining outcomes.

Generally, the micro-pore processing tools have a large length-to-diameter ratio and poor rigidity and are prone to such problems as orifice damage and drill bit fracture when the axial force is too large in the processing. To reduce the cutting force in the micro-pore drilling and improve the tool life and hole processing quality, some scholars choose to reduce the hardness of ceramic or low-hardness ceramic for processing. For example, Wang et al.[20] conducted drilling experiments on pre-sintered Al_2O_3 ceramics and studied the hole processing quality and tool wear under different sintering temperatures. Chang et al.[21] made high aspect ratio (11.64, 15.36) micropores in nitride ceramics by segmented processing (∅64 μm, ∅55 μm). The influence of processing parameters on the hole size characteristics is studied.

In addition, processing technology has also been studied by relevant scholars, and the most commonly used method is drilling. For example, Dar et al.[22] carried out micro hole drilling experiments on fully sintered Al_2O_3 ceramics by pecking drilling with shallow depth continuous cooling, studied the influence of processing parameters such as spindle speed, feed rate, and fallback distance on hole size characteristics, and obtained the optimal parameter combination through Taguchi analysis. When machining BK7 optical glass, Ma et al.[23] compared it with traditional drilling, and the results show that the hole outlet damage can be greatly reduced by machining with the borer, and the reciprocating borer can improve the chip removal condition and the hole wall quality. The return stroke after each cutting also enables the drill to be completely cooled, reducing the machinability of the tool caused by the heat generated in the drilling, and prolonging the service life of the tool.

The aforementioned study explored effects of diverse machining methods, techniques, and parameters on hole machining quality. Furthermore, while the machined apertures are predominantly at the millimeter scale, there remains a notable research gap in the area of submillimeter holes. Therefore, in this paper, the diamond-coated drill bits with sub-millimeter diameter are used to peck drill micro-holes on fully sintered zirconia ceramic. The drilling force, tool wear and quality of hole entrance and exit are studied and analyzed in the test. The influences of peck drilling parameters on the machining process are investigated. Scanning electron microscopy technology is applied to define the tool wear mechanism.

1 Experimental Setups

1.1 Workpiece material and test setups

The workpiece material used in this study is a commercial ZrO_2 ceramics, mainly consisting of insulating tetragonal polycrystalline zirconium oxide (Y-TZP) partially stabilized with yttria. After a final sintering process at a temperature of 1 350—1 500 ℃, the material provides a high hardness about 1 200 HV10 and a relatively high fracture toughness. The workpiece is shaped with an overall size of 10 mm×10 mm×1 mm. Table 1 and Table 2 show the chemical composition and mechanical properties of the material, respectively.

As shown in Fig.1, the ∅0.5 mm hole drilling tests are conducted on a five-axis precision machining center (Mikron MILL E 500U, Swiss). The machine tool adopts C type cast iron body structure

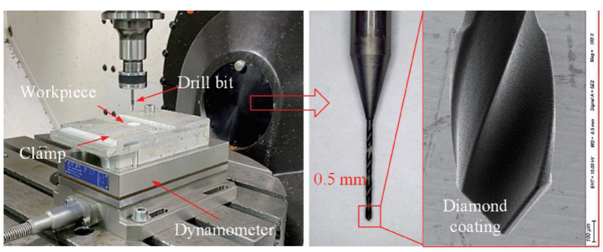
Table 1 Chemical composition of workpiece

Composition	Weight percentage/%
ZrO_2	<96
Y_2O_3	>4
Al_2O_3	<1
SiO_2	<0.02

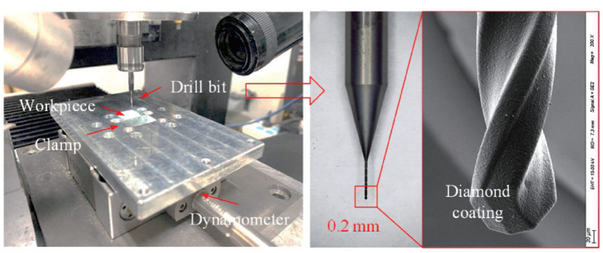
Table 2 Mechanical properties of workpiece

Property	Value
Density $\rho/(g \cdot cm^{-3})$	6.03
E-modulus E/GPa	210
Fracture toughness $K_{IC}/(MPa \cdot m^{1/2})$	10
Vickers hardness HV10 $H/(kg \cdot mm^{-2})$	1 200

with high rigidity and stability, which can ensure the machining accuracy and process stability. The maximum rotating speed of the spindle is 12 000 r/min. While the ∅0.2 mm hole drilling tests are carried out on a self-developed three-axis micro milling center. The machining center features a linear motor-driven platform with high-precision positioning capabilities. The maximum spindle rotating speed is about 100 000 r/min, which can ensure a certain cutting speed when the tool diameter is very small.



(a) Test system of ∅0.5 mm holes (b) ∅0.5 mm diamond-coated drill bit



(c) Test system of ∅0.2 mm holes (d) ∅0.2 mm diamond-coated drill bit

Fig.1 Experimental setups

The drilling tools used are CVD diamond-coated micro drill bits with diameters of 0.2 mm and 0.5 mm. The tool matrix is cemented carbide and the thickness of the diamond coating is approximately 8—10 μm. Part of specific parameters of drill bits are listed in Table 3.

Table 3 Specific parameters of the drill bit

Parameter	S_1	S_2
Drill diameter D/mm	0.5	0.2
Shank diameter d/mm	3.175	3.175
Helical angle θ/(°)	30	30
Effective length L_e/mm	7	3

To monitor the cutting force during drilling process, the Kistler dynamometer system is used. The dynamometer is installed on the base of the machine tool, and then the workpiece is fixed on the aluminum base plate through high-strength adhesive. In addition, SEM is used to observe the tool wear of the drill bit and the quality of the hole outlet.

1.2 Experimental conditions and procedures

Since the diameter of the processed hole is relatively small and the depth-diameter ratio is about 2—5, continuous drilling is not conducive to the removal of chips. Therefore, the intermittent pecking drilling process is adopted in the machining process experiment, as shown in Fig.2. The conventional continuous-feed drilling process for through-holes is modified to adopt a peck drilling strategy. In this approach, the drill bit advances to a predetermined depth increment (fixed step distance d_s), then fully retracts to the workpiece surface after each penetration. This peck-and-retract cycle repeats iteratively until the full hole depth is achieved.

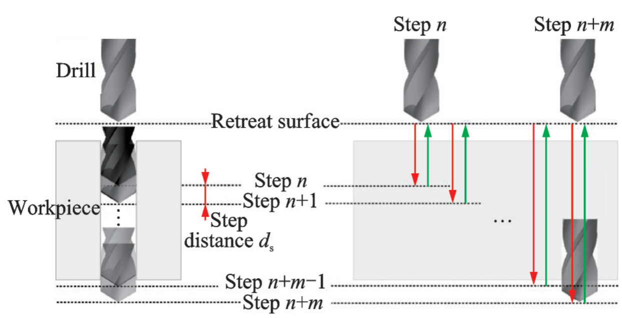


Fig.2 Schematic diagram of peck drilling processing

Zirconia ceramics have high hardness and great brittleness, and they are typical difficult-to-cut materials. In addition, since the diameter of the drill bit is at the sub-millimeter level and the overall structure is relatively long and slender. It is easy to be broken under the action of the drilling force during drilling process. Based on the relevant literature reports[24], both the feed speed f and the stepping distance d_s are main factors affecting the cutting force. Moreover a relatively high spindle speed (n, r/min) needs to be selected to obtain a certain cutting speed. Therefore, feed speed, step distance, and spindle speed are selected as key process parameters in this study. Ductile-regime machining of brittle materials is achievable when the undeformed chip thickness is controlled below the material-specific critical value, at which point material removal transitions from brittle fracture to plastic flow[25]. At the same time, a relatively small feed rate (f, mm/min) needs to be selected so that the material can be removed in the ductile regime, in order to control the drilling force at a relatively low level and ensure the overall stability of the drilling process. The test parameters are shown in Table 4. Each test group is repeated three times. After the experiments, a microscope and a scanning electron microscope are used to observe the machining quality and microscopic morphology of micro-holes, as well as the tool wear of the diamond-coated drill bits.

Table 4 Test parameters of drilling processes

Test No.	Tool diameter D/mm	Spindle speed n/(r•min^{-1})	Feed speed f/(mm•min^{-1})	Step distance d_s/mm
1		15 000	0.5	0.01
2		15 000	0.5	0.02
3		15 000	0.5	0.03
4	0.2	15 000	0.7	0.01
5		15 000	0.9	0.01
6		17 500	0.5	0.01
7		20 000	0.5	0.01
8		9 500	1.2	0.02
9		9 500	1.5	0.03
10		9 500	1.8	0.04
11		8 500	1.2	0.03
12	0.5	8 500	1.5	0.04
13		8 500	1.8	0.02
14		7 500	1.2	0.04
15		7 500	1.5	0.02
16		7 500	1.8	0.03

2 Results and Discussion

2.1 Analysis of drilling force

2.1.1 Analysis of drilling force characteristics

Fig.3 shows a typical time-domain diagram of three-directional drilling force signals throughout the entire process when a ∅0.5 mm diamond coated drill bit is used to drill zirconia ceramics under n=7 500 r/min, f=1.5 mm/min, and d_s=0.02 mm. As can be seen from Fig.3, the fluctuations of F_x and F_y signals are very small, and the amplitudes are basically within 3 N. However, the axial force F_z is relatively large, obviously presenting the characteristics of intermittent drilling during the pecking drilling process. Judging from changes in amplitude and interval, at the initial stage of drilling, as the drill bit gradually penetrates, the axial force gradually increases. Subsequently, it enters a stable drilling process and fluctuates within a certain range. In the later stage of drilling, the feed rate decreases, and as the drill bit gradually exits, the volume of the material removed by the main cutting edge of the drill bit continuously decreases. Therefore, the axial force gradually decreases.

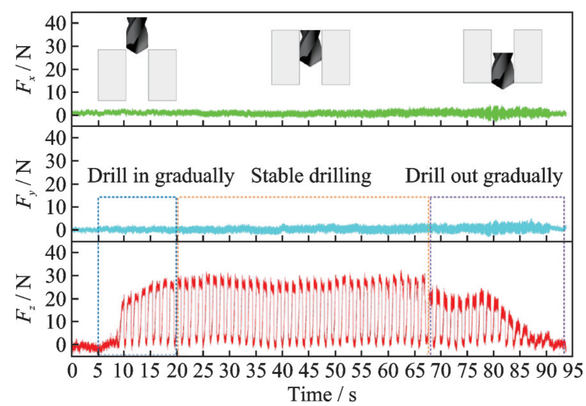


Fig.3 Signal diagram of drilling force in complete peck drilling process

Fig.4 shows a typical diagram of the axial force signal for a single step. As can be seen from Fig.4, the drilling force signal initially rises slowly for a certain period. Subsequently, it stabilizes and fluctuates within a certain range. Finally, as the tool is retracted rapidly, the axial force returns to zero.

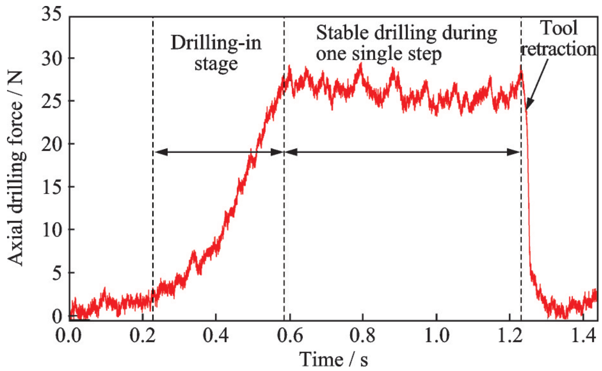


Fig.4 Typical axial force signal of a single feed cycle

2.1.2 Effect of drilling parameters on the axial force

Fig.5 and Fig.6 show the influence of the drilling parameters on the axial force F_z when drilling zirconia ceramics with ∅0.2 mm and ∅0.5 mm drill bits, respectively.

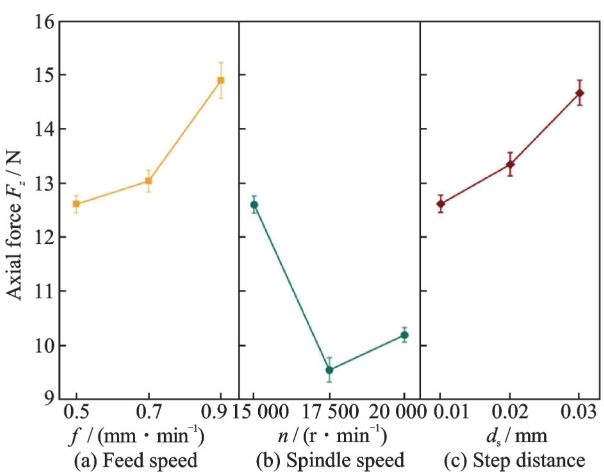


Fig.5 Effects of drilling parameters on the axial cutting force with ∅0.2 mm drill bit

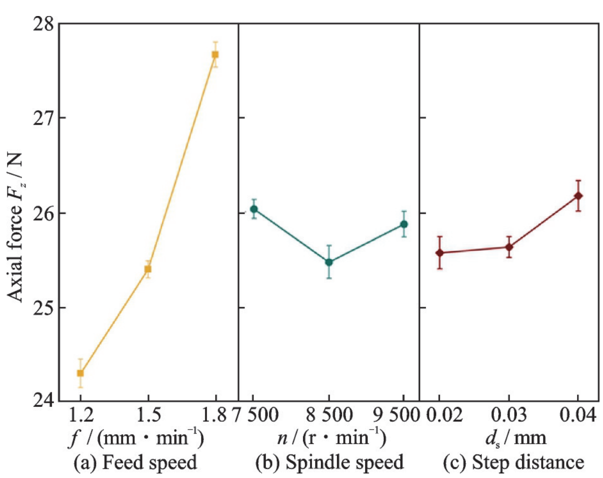


Fig.6 Effects of drilling parameters on the axial cutting force with ∅0.5 mm drill bit

It can be seen from Fig.5(a) that as the feed speed increases, the axial force gradually increases. When the feed speed f increases from 0.5 mm/min to 0.7 mm/min, the axial force F_z increases by 0.43 N, while the feed rate increases from 0.7 mm/min to 0.9 mm/min, the axial force increases by 1.86 N, showing an increase of more than four times. Fig.6(a) also shows a similar change of cutting force. Generally speaking, the increase in feed speed will increase the cutting thickness per revolution in drilling, and the load on the cutting edge of the bit will also increase.

Although increasing the feed speed can reduce the time required and improve the processing efficiency, it is necessary to take into account the wear of the drill bit and the stability of the processing process. At the same time, because the drill bit diameter is small and large axial force may cause the risk of breaking of drill bit, so it is recommended to use smaller parameters for feed speed.

Fig.5(b) and Fig.6(b) show changes of axial force F_z at different spindle speeds. It is shown that as the spindle speed increases, the axial force first decreases and then increases. When the spindle speed is relatively high, the relative movement speed between the tool and the workpiece material increases, leading to an increase in tool wear. When the spindle speed is relatively low, the cutting speed of the tool decreases, resulting in an increase in the axial force. Therefore, it is recommended to select a moderate spindle speed.

Another influencing factor is the feed step distance. Fig.5(c) and Fig.6(c) show the influence of different step distances on the axial drilling force when two types of drill bits are used. As can be seen from the figures, in both cases, the changes in the axial drilling force are similar, and it increases with the increasing of the step distance.

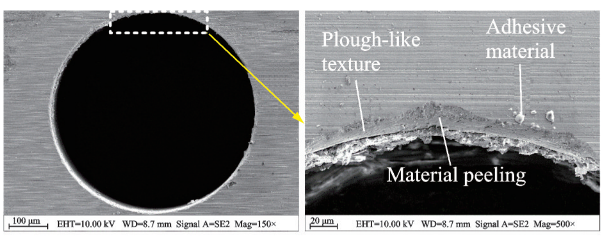
There may be several reasons for this phenomenon. On one hand, when the step distance d_s increases, continuous drilling will increase the friction and extrusion between the cutting tool and the zirconia material, thus increasing the axial force. On the other hand, when the single-step distance increases, the drilling time becomes longer, resulting in more chips accumulating in the hole, which will cause an increase in the axial force.

2.2 Analysis of morphology at micro-hole entrance and exit

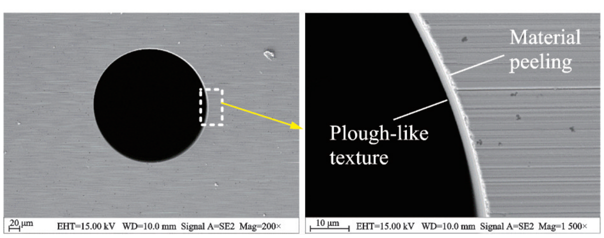
2.2.1 Analysis of morphology at hole entrance

Fig.7 shows typical morphologies of micro hole entrances with different diameters. As shown in Fig.7(a), the overall morphology of the entrance of the hole with a diameter of 0.5 mm is presented. The shape of the hole is very regular, and there are no obvious defects on the overall entrance surface of the hole. From the locally enlarged image, it can be seen that there is a slight fragmentation at the edge of the entrance. The material is removed in the form of brittle failure, and a shape similar to a chamfer is formed. In addition, some chip residues are adhered to the hole opening.

However, in Fig.7(b), the entrance of the hole with a diameter of 0.2 mm shows better quality. As can be observed from the locally magnified image, the edge of the hole is very smooth, and there is no brittle failure area similar to that at the edge of the 0.5 mm hole. It may because that the feed rate of drilling process in this hole is only 0.5 mm/min, and the lower feed rate enables the material to be removed in the ductile regime, resulting in better machining quality.



(a) ∅0.5 mm: n=9 500 r/min, f=1.2 mm/min, d_s=0.02 mm

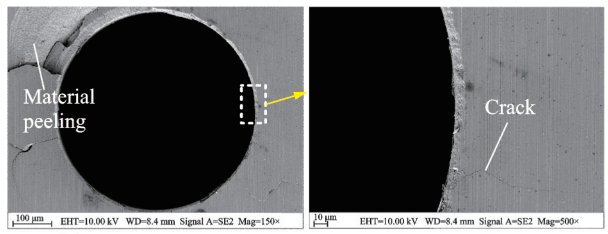


(b) ∅0.2 mm: n=15 000 r/min, f=0.5 mm/min, d_s=0.01 mm

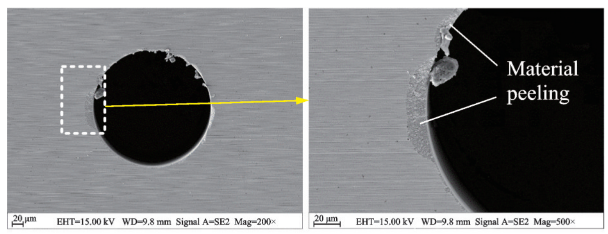
Fig.7 SEM images of micromorphology at hole entrance

2.2.2 Analysis of morphology at hole exit

Different from the entrance, the quality of the micro-hole exit varies greatly. Fig.8 shows morphologies of hole exits with different diameters. As shown in Fig.8(a), the exit morphology of the 0.5 mm hole is presented, which is drilled with big feed rate and step distance. It can be seen that a large-area chipping morphology appears in a specific area, accompanied by obvious crack propagation. The material in the chipping area undergoes massive brittle fracture. This is mainly because the bottom material is squeezed by the drill bit during the feed. When the drill bit exits, the material is broken under the action of drilling force.



(a) ∅0.5 mm: n=9 500 r/min, f=1.5 mm/min, d_s=0.03 mm



(b) ∅0.2 mm: n=20 000 r/min, f= 0.5 mm/min, d_s=0.01 mm

Fig.8 SEM images of micro morphology at hole exit

During the drilling process, when the drill bit gradually drills out of the bottom of zirconia ceramic, the material in the exit area will undergo tensile failure under the pressure of the drill bit. At this time, with the wear of drill bit, the cutting force will also gradually increase, and the thickness of ceramic material to be removed will gradually decrease. When the thickness is small to a certain extent, the stress of the remaining material at the hole outlet will be lower and lower. When the tensile stress caused by the drill bit feeding on the material gradually exceeds the extreme value of the fracture stress of the material, cracks begin to appear inside the material, and as cracks continue to expand, serious edge collapse occurs at the hole exit.

Similarly, at the exit of the 0.2 mm hole, there is also chipping of the material within a certain range. Compared with the 0.5 mm hole, the chipping area is much smaller. This also shows that under the condition of a smaller feed rate, the range of chipping at the exit is also smaller.

2.2.3 Analysis of the chipping size at hole exit

In the drilling process of zirconia ceramics, the pattern of the chipped edge at the hole exit is usually presented in an irregular shape, and the size is rather random and unpredictable. Therefore, as shown in Fig.9, the maximum dimension of the chipped edge C is measured as one of the processing quality standards[26]. The calculation formula is shown as

$$C=(D_{max}-D)/2 \quad (1)$$

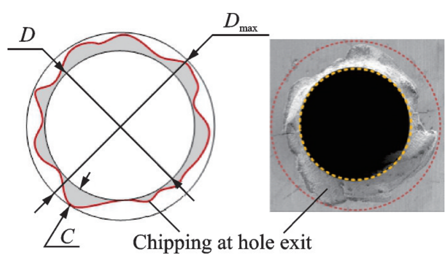


Fig.9 Measurement method of edge chipping size

Fig.10 shows the influence of drilling parameters on the chipping size at the exit of the micro-hole. It can be seen from Fig.10 that the feed rate has the greatest influence on the chipping size. As the feed rate increases from 1.2 mm/min to 1.8 mm/min, the chipping size increases from 27 μm to about 57 μm. The reason may be that when the feed rate increases, the volume of material removed per unit time increases, and the axial force increases, which leads to an increase in the chipping size.

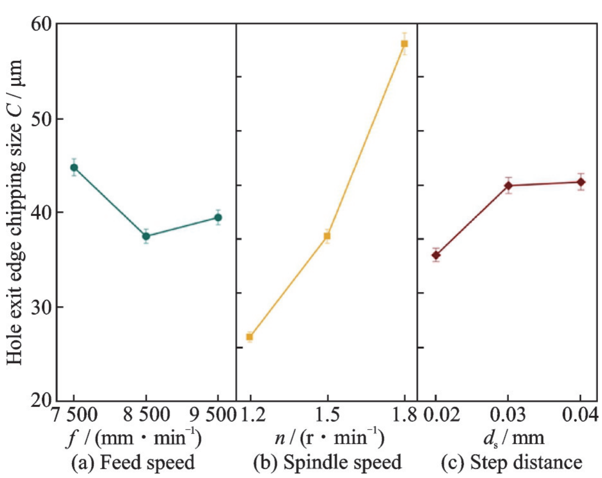


Fig.10 Effect of drilling parameters on the chipping size at exit of ∅0.5 mm holes

As the spindle speed increases, the chipping size at the hole exit first decreases and then increases. As the step distance increases, the chipping size also gradually increases. The above rules are similar to the analysis results of the influence of machining parameters on the axial force. According to the analysis of chipping generation, the chipping size should increase with the increasing of the axial force. Therefore, in order to reduce the chipping size at the exit of the micro-holes drilled in zirconia ceramics, firstly, a lower feed rate should be selected. Secondly, a smaller step distance should be chosen, and the spindle speed should be controlled within a moderate range.

2.3 Tool wear analysis

In this study, diamond-coated drill bits are used to drill zirconia ceramics. Since zirconia ceramics are typical difficult-to-cut materials, even when diamond-coated cutting tools are employed, the tool wear and failure are still relatively severe.

Fig.11 shows the micro-morphology and local enlarged SEM images of the ∅0.5 mm drill bit processed with different processing parameters. It can be seen from Fig.11 that under different processing parameters, the drill bit wear morphology characteristics are relatively similar, and the wear is mainly concentrated on the main cutting edge and the front and rear cutting edges.

In conventional processing of engineering ce-

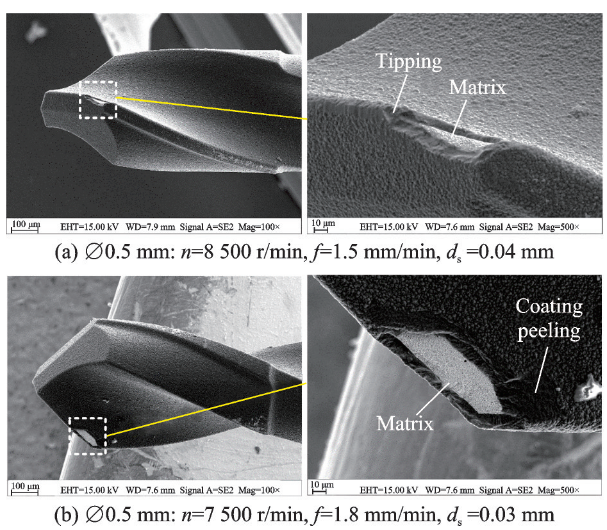
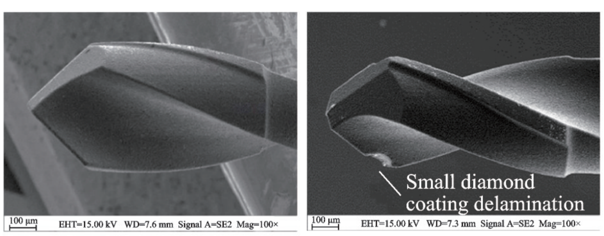


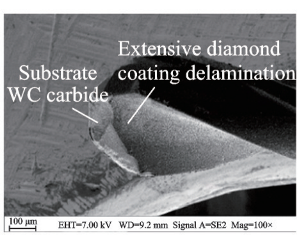
Fig.11 SEM images of microscopic morphology of coating delamination

ramic materials, the material removal mechanism differs from that of metal. Under the extrusion of the cutting edge, chips are generally removed in the form of brittle fracture and do not contact with the rake face of the drill, so the rake face is slightly worn[27]. However, the cutting thickness of this machining is far less than critical cutting thickness, and the material is removed in a ductile mode. Therefore, during the drilling process, a small part of tiny chips generated by the ZrO_2 ceramic will stay in the contact area between the tool and the workpiece. With the progress of drilling, serious friction occurs in the contact area, making the cutting edge with lower strength wear first.

Fig.12 shows the change process of tool wear of the ∅0.5 mm diamond-coated drill bit after continuous drilling under specific parameters. As can be seen from Fig.12, the diamond-coated drill bit has gone through several stages, including the micro delamination of the diamond coating, large-scale delamination of coating, and wear of substrate material. This is similar to the wear and failure process of most diamond-coated cutting tools[19, 28]. Fig.12(a) shows the appearance of the tool in the initial stage of drilling. The coating is intact, and there is no exposure of the substrate material. Fig.12(b) shows that after drilling several holes, the coating shedding occurs at the cutting edge, exposing the substrate material. Fig.12(c) shows that in the later stage of drilling, a large area of the coating on the drill bit sheds, exposing a large amount of cemented carbide substrate material. Moreover, after the substrate material at the drill tip loses the protection of the coating, it suffers from severe wear.



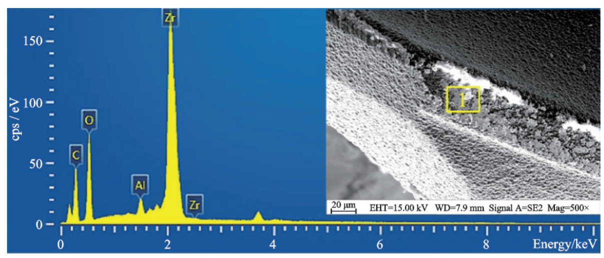
(a) Initial stage of drilling (b) Small-area coating delamination



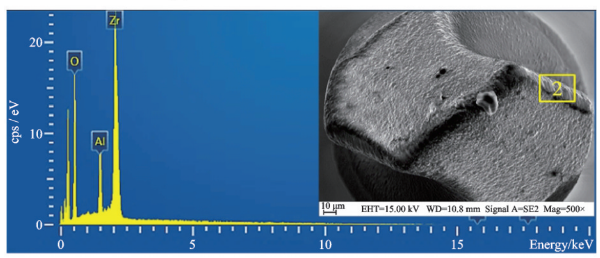
(c) Large-scale coating delamination and substrate wear

Fig.12 SEM images of typical wear morphology of the drill bit at different stages under n=9 500 r/min, f=1.2 mm/min and d_s =0.02 mm

During the drilling process of zirconia ceramic, there is chip adhesion on the diamond-coated bit. SEM images of bit wear after processing and EDS energy spectrum analysis are shown in Fig.13. It can be seen from Fig.13 that there is white adhesive in the wear area of the rake and flank faces of the tool. According to the analysis results, the white binders at these two points are mainly contains Zr and Al elements, while the diamond coating mainly contains C element. It can be inferred that the adhesive on the surface originates from the zirconia ceramic and the aluminum plate substrate.



(a) Adhesion on the flank faces



(b) Adhesion on the cutting edge

Fig.13 Wear profile and energy spectrum analysis of the drill bit

The wear of the drill bit has an important impact on the axial drilling force and the machining quality on the hole exit. As shown in Fig.14, it is the variation of the drilling force with the number of drilled holes during the process of continuously drilling multiple holes with the same drill bit. As can be seen from the figure, with the increase in the number of drill holes, the axial force generally shows an upward trend, and the variation range of the axial force is very obvious. The axial force gradually increases from 22.4 N to 54.7 N, with an increase rate as high as 144.2%. This is mainly because as the number of drill holes increases, the drill bit continuously wears during processing. The cutting edge at the drill tip becomes blunt, and the contact area between the flank face of the drill bit and the zirconia ceramic increases. The friction between the two gradually increases, leading to a multiple increase in the drilling axial force.

Due to the increase in axial force, the edge chipping phenomenon at the exit of the machined hole has become increasingly severe. SEM images in Fig.14 show the morphology of edge chipping at the hole exit. From the 1st hole to the 6th hole, the size of exit edge chipping tends to increase, growing from the initial 23 μm to about 135 μm.

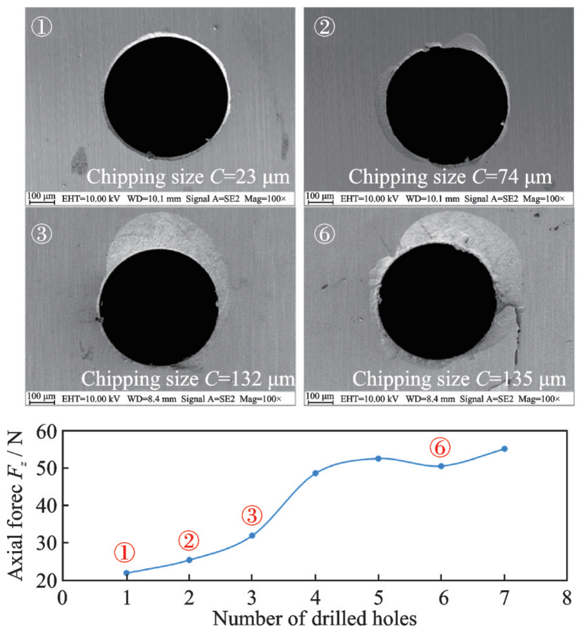


Fig.14 Influence of tool wear on drilling force and exit edge chipping

4 Conclusions

Based on the experimental study, the material removal process of fully sintered zirconia ceramic is investigated and effects of different drilling parameters on the axial cutting force, quality of hole exit, and tool wear of diamond coated drill bits during peck drilling of zirconia ceramic are revealed. From experimental results and analysis, the following conclusions can be drawn:

(1) During the peck drilling process, the axial force changes significantly, which has a great impact on the drilling process and the quality of micro-holes. Among experimental parameters, the feed rate f has the greatest influence on the axial force. The axial force increases with the increasing of the feed rate f and the step distance d_s. It is recommended to use a smaller feed rate, a shorter step distance, and a moderate spindle speed for micro-hole drilling.

(2) Under the action of the axial force, the damage at the hole exit of micro-holes in zirconia ceramics is more severe than that at the entrance. Chipping and cracks often exist, which affect the machining quality of holes. The bigger the feed rate is, the greater the generated axial force will be, resulting in a larger chipping area at the exit. On the premise of ensuring the machining efficiency, a smaller feed rate should be selected.

(3) The wear of diamond-coated drill bits is similar to that of other coated tools, and coating chipping is likely to occur at the main cutting edge. During the entire drilling process, tool wear can be divided into the initial stage, minor coating peeling stage, and extensive coating peeling stage, resulting in substrate wear. Energy spectrum analysis shows that during drilling, zirconia ceramics will adhere to the tool cutting edge, causing adhesive wear. Moreover, the wear of the drill bit will significantly affect the chipping size of hole exit.

(4) The wear of the drill bit has an important impact on the axial drilling force and the chipping size at the hole exit. In this study, it is found that the axial force gradually increases from 22.4 N to 54.7 N, with an increase rate as high as 144.2%. The size of exit edge chipping also tends to increase, growing from the initial 23 μm to about 135 μm.

In order to deeply understand the micro-hole drilling of zirconia ceramic, more research should be carried out in the future on aspects of optimization of feed parameters, material removal mechanism, and suppression of machining damage at hole exit. For instance, explore a novel variable feed rate process that reduces the feed speed when the drill is about to exit the workpiece, thereby decreasing axial force and minimizing hole exit damage. Establish measurement criteria for quantitative analysis of drill wear to provide more effective references for investigating the wear mechanism of drill bits.

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Author contributions Dr. **BIAN Rong** designed the study, complied the models, conducted the analysis, interpreted the results and wrote the manuscript. Mr. **ZHOU Junwei** carried out machining tests, analyzed data and co-wrote the manuscript. Prof. **DING Wenzheng** and Mr. **XU Youfeng** conducted the analysis of tool wear. Dr. **KHAN Aqib Mashood** and Dr. **CHEN Ni** supplied necessary support for the testing equipment, and assisted in editing technical details of the manuscript. All authors commented on the manuscript draft and approved the submission.

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金刚石涂层钻头微孔啄钻氧化锆陶瓷试验研究

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摘要:氧化锆(ZrO_2)陶瓷材料因其具有高强度、高硬度和优异的耐高温等独特性能,已在多个领域得到广泛应用。然而,目前针对氧化锆陶瓷材料的高质量微孔加工仍是一项重大挑战。本文采用金刚石涂层钻头,对氧化锆陶瓷进行了直径0.2 mm和0.5 mm的微孔啄钻加工试验,分析了钻孔过程中力信号的特征、钻孔参数对钻削力和孔出口崩边尺寸的影响,以及金刚石涂层钻头的刀具磨损阶段特征。试验结果表明,在氧化锆陶瓷微孔加工时,轴向力与出口处崩边尺寸呈正相关,轴向力随着进给速度和步进距离的增加而增大;钻头的磨损对孔出口质量有显著影响,随着连续钻削7个孔,轴向力增加了144.2%,出口处边缘崩屑尺寸从约20 μm增加到130 μm以上。本研究可为提高该材料的微孔加工质量提供有价值的参考。

关键词:氧化锆陶瓷;金刚石涂层;啄钻;崩边;刀具磨损