Vol. 19 No. 4 CHINESE JOURNAL OF AERONAUTICS November 2006

Experimental Research on the Ground Surface Quality of Creep Feed Ultrasonic Grinding Ceramics (Al_2O_3)

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Abstract: In order to grind the ceramic blade surface with the Numerical Control contour evolution ultrasonic grinding method using the simple shape grinding wheel, primary comparative experiments of creep feed grinding with and without ultrasonic vibration were carried out to grind Al_2O_3 ceramics so as to implore the effects of different process parameters on the machined surface quality. It can be concluded that when the direction of ultrasonic vibration is parallel to the direction of creep feed, the value of the surface roughness will be decreased; otherwise the surface quality will become worse. With the ultrasonic grinding method, the slower feed-rate, the smaller grinding depth, the higher grinding speed and the compound feed grinding method should be applied in order to improve the surface quality. The creep feed grinding mechanisms with and without ultrasonic vibration were analyzed theoretically from the experimental results. With the selected grinding parameters resulted from the experiments, the feasibility experiment of ultrasonic grinding ceramic blade surface was carried out.

Key words: ceramics; ultrasonic grinding; creep feed grinding; surface quality; profile grinding

Al_2O_3 陶瓷蠕动进给超声磨削加工表面质量的试验研究. 郑建新，徐家文. 中国航空学报(英文版), 2006,19(4): 359-365.

摘　要：为探索利用简单形状砂轮对陶瓷材料进行数控展成型面超声磨削，通过对 Al_2O_3 陶瓷进行蠕动进给超声磨削和机械磨削对比试验研究，探索各加工参数对磨削表面质量的影响规律。结果表明：超声振动方向与蠕动进给方向平行时可降低表面粗糙度值，而超声振动方向与蠕动进给方向垂直时则不利于改善加工表面质量；在超声磨削条件下，为了提高加工表面质量，应采取较小的磨削深度、较低的进给速度和适当高的磨削速度以及复合进给磨削方式。结合试验结果理论分析了蠕动进给超声磨削和蠕动进给机械磨削加工机理，并根据试验结果选择磨削参数进行了陶瓷叶片型面超声磨削的可行性试验。

关键词：工程陶瓷；超声磨削；蠕动磨削；表面质量；型面磨削

文章编号：1000-9361(2006)04-0359-07　　**中图分类号：**V261.2^{+}5;TG663　　**文献标识码：**A

Al_2O_3 ceramics are the new ones that have the widest application and greatest production among the oxide ceramics at present. They are applied widely in the fields of petroleum industry, chemical engineering, aerospace engineering, automobile industry and biomedicine industry, etc., owing to their unique physical and mechanical properties, such as high mechanical strength and hardness, big insulation resistance, high wear resistance, high corrosion resistance and chemical stability at elevated temperatures [1-3]. But the machining of ceramics is the major challenge for their high hardness, high brittleness and low fracture toughness[4]. Of the total production costs for ceramic components, machining can account for 30%-60% and sometimes even up to 90%[5]. Obviously the machining of ceramics has hindered their further applications. So the urgent work is to explore preferable processing technique with high precision,

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Received date: 2005-12-03; Revision received date: 2006-03-21
Foundation item: Jiangsu Natural Science Fund of China (BK2001048)

technique with high precision, high efficiency and low cost.

Nevertheless, up to the present day grinding is used as the major method to finish ceramics. Although quite acceptable surface quality of grinding can be achieved, the low processing efficiency and high manufacturing cost are insufferable. In the past few years and till now, the ultrasonic grinding attracts extensive attention again as an important technique to grind advanced ceramics[6,7]. Ultrasonic grinding is a hybrid machining process that combines the diamond grinding and the ultrasonic machining, which can improve the grinding efficiency and quality, so as to meet the special case of machining brittle materials including ceramics. While creep feed grinding was originated by ELB Grinding Machine Company in West Germany in 1958, as a high-efficiency grinding technique it has been successful in grinding hardened steel[8].

In order to grind the integral wheel with variable cross-section tortuous blades on the typical ceramic materials of Al_2O_3 with the Numerical Control contour evolution ultrasonic grinding method using the simple shape grinding wheel, comparative experiments of creep feed grinding with and without ultrasonic vibration were carried out to grind Al_2O_3 ceramics on the Numerical Control ultrasonic machining setup developed by our lab to analyze the effects of different process parameters on the ground surface quality, so as to implore the adaptable process parameters for the ultrasonic grinding blade profile later.

1 Experimental Setup

The numerical control ultrasonic grinding machine utilized in this experiment is shown in Fig.1, which was developed by our research group. The worktables of the machine tool are driven by the stepper motors, so the straightway motions along x, y and z axes and the rotary motion around z axis can be realized. The grinding wheel is driven by an inverter-fed motor, and can rotate with the speed changing from 100 r/min to 20 000 r/min stepless. In this experiment the specimen was excited with ultrasonic longitudinal vibration. Compared to the conventional machining method with ultrasonic vibration of the grinding wheel, such machining method with vibration of the specimen can simplify the whole system. When the grinding wheel is excited by the ultrasonic vibration, the ultrasonic acoustic system should be fixed on the spindle in the conventional ultrasonic machining tool, so the connecting elements including the carbon brush are needed so that the acoustic system may rotate with the spindle, which makes it difficult to design the machining system. While when the horn is connected with the specimen in the device used in this study, it may lead to the simplification of the system design.

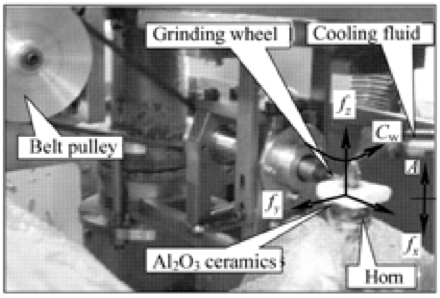


Fig.1 Numerical control ultrasonic grinding machine

2 Experimental Conditions

Some avenues such as ductile regime grinding and high-speed grinding are pursued in damage-free grinding ceramics. The damage-free ground surface is also achieved through ultrasonic assisted grinding a Pyrex glass specimen with decreasing the cutting speed and improving the vibration frequency using big abrasives[3].

The major affecting parameters on the ground surface's quality include the grinding depth, the grinding speed, the feed-rate, and the grit size, etc. In fact, the contact between the abrasives and the specimen is discontinuous in the ultrasonic grinding process, and the critical grinding speed is related with the ultrasonic vibration amplitude A and frequency f, so it accords with the vibration cutting theory, which is to say that the critical grinding speed V_{slim} can be expressed as $V_{\mathrm{slim}} \leqslant 2\pi Af$ [9]. Such expression can not be applied mechanically when the complexity of ultrasonic grinding process is taken into account as this expression is conducted with single blade cutting. But the critical grinding speed is supposed to exist in the process of ultrasonic grinding. So it is not suitable to take too large grinding speed. As in the one hand, this experiment is a part of the preparation for the ultrasonic grinding ceramics blades using grinding wheel with simple shape, and in the other hand, in order to compare the creep feed grinding ceramics with/without ultrasonic vibration conveniently, it is advisable to refer the work of other researchers when selecting the appropriate grinding parameters[3, 4,10-15]. In this experiment, the grinding depth is 0.1 mm-0.5 mm, which is larger than the critical grinding depth in the ductile regime grinding ceramics, and smaller than that of the creep feed mechanical grinding slightly. The grinding speed is slower than 6 m/s, and the feed rate is 0.5 mm/min-2.5 mm/min. The grinding wheels are some electroplated diamond wheels: the diameter of the grinding wheel is 3 mm (adaptable to grind slots between the blades on the integral wheel)with the grain sizes #120 and #240 and the diameter of the grinding wheel is 15.5 mm (adaptable to grind the rough surface of the integral wheel)with the grain size #180, and the concentrations of all abrasive grains are 75%. The amplitude of ultrasonic vibration A is about 5 μm -7 μm, and the vibration frequency f is 19.96 kHz. The ordinary water-base cooling fluid was selected as the coolant. Detailed experimental conditions are shown in the Figs. 2-6, where

R_{a} — surface roughness (μm);

a_{p} — given grinding depth (mm);

n — rotational speed of the grinding wheel (rad/min);

V_{s} — peripheral speed of the grinding wheel (m/s);

f_x and f_z — feed rates of worktables of the machine tool along x and z axes (mm/min);

f_y — seesaw motion feed rate of the worktable of the machine tool along y-axis in the stroke of 1 mm (mm/min);

C_{w} — rotational speed of the worktable of the machine tool around z axis ((°)/min);

USG — Ultrasonic Grinding;

MG —Mechanical Grinding.

Only one grinding parameter was changed and other grinding parameters were fixed in each experiment so as to compare the grinding effects with and without ultrasonic vibration conveniently. The ultrasonic grinding and the mechanical grinding were carried out one by one with the same grinding parameters and the same grinding wheel so as to avoid the effect of the abrasion of the grinding wheel. And material finishing was omitted. After each experiment the grinding wheel was replaced with a new one, so wheel dressing may be omitted.

3 Results

The surface finish and integrity of the ground surface quality of the specimens were assessed by the measurement of surface roughness using a roughometer and by observing of the surface topography using a scanning electron microscope (SEM). The value of average roughness R_{a} is the mean of five measured values normal to the machined direction.

3.1 Effects of the grinding parameters on the surface roughness

In the process of creep feed ultrasonic grinding, the effects of the grinding parameters on the ground surface roughness are the same as those in the process of creep feed mechanical grinding, as is shown in Figs.2-4. That is to say, the deeper the grinding depth and the faster the grinding feed rate, the larger the value of the ground surface roughness; and the greater the rotational speed of the grinding speed(scilicet, the peripheral speed of the grinding wheel), the smaller the value of the ground surface roughness.

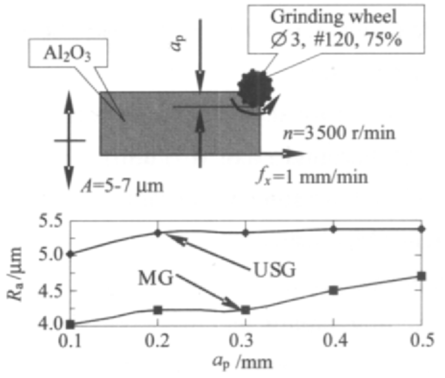


Fig.2 Effects of the grinding depth on the surface roughness

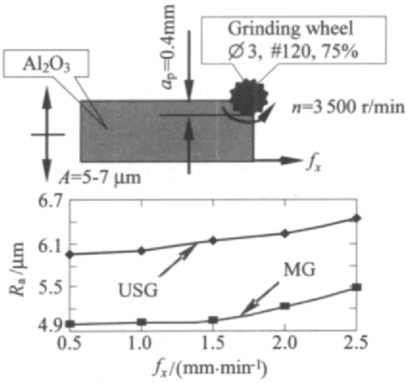


Fig.3 Effects of the feed-rate on the surface roughness

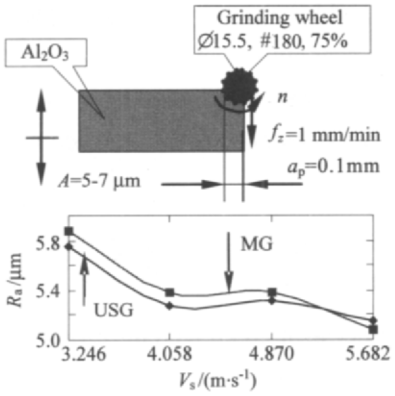


Fig.4 Effects of the grinding speed on the surface roughness

3.2 Effects of the feed method on the surface roughness

Adding a seesaw motion f_y to the worktable when the grinding wheel moved straightly along z axis (shown in Fig.2), which may be called compound feed motion, the value of surface roughness will be decreased evidently in the process of creep feed grinding, as is shown in Fig.5. The direction of the seesaw motion should be normal to the direction of the grinding wheel's main feed motion f_z. Compared Fig.5 with Fig.2, when adding the compound feed motion to the worktables while other grinding parameters are unchanged, the value of the ground surface roughness decreases from 4.018 μm -5.38 μm to even lower than 1.768 μm. Further experiments indicates that the value of the ground surface roughness can be decreased farther if increasing the seesaw motion feed rate f_y of the worktable (for example: f_y =3 mm/min, the stroke 1 mm).

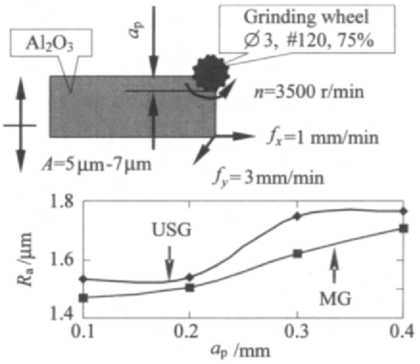


Fig.5 Effects of the grinding mode on the surface roughness

3.3 Effects of the direction of the ultrasonic vibration on the surface roughness

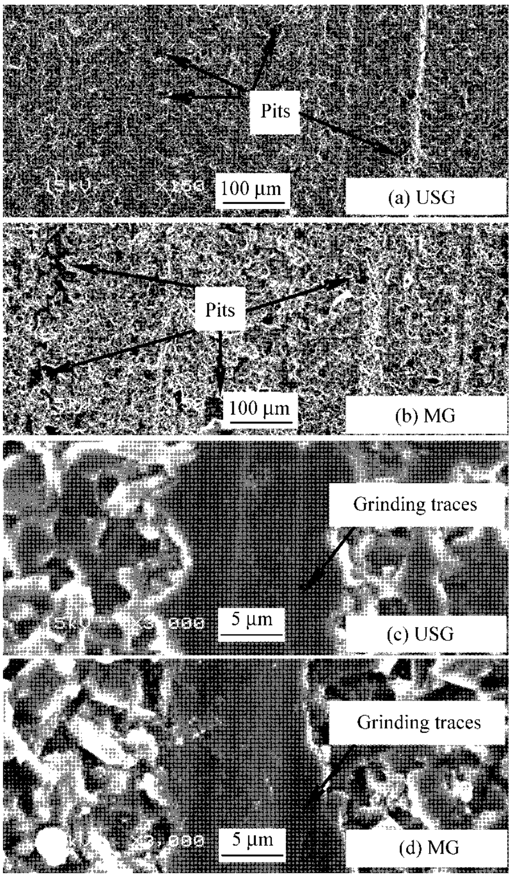
The direction of the ultrasonic vibration has an effect on the surface roughness. The results shown in Fig.2 and Fig.3 indicate that when the direction of the vibration is normal to the direction of creep feed, the value of the ground surface roughness gained by ultrasonic grinding is always larger than that of the machined surface quality gained by the mechanical grinding in the same experimental conditions, and the maximum of the discrepancy is up to 1.095 μm (shown in Fig.2 when the grinding depth a_p is 0.2 mm). While when the direction of vibration is parallel to the direction of creep feed, the value of the machined surface roughness gained by ultrasonic grinding is declined slightly compared to that gained by the mechanical grinding at the same experimental conditions, as is shown in Fig.4. But when the peripheral speed of the grinding wheel Vs is up to 5.682 m/s, the value of the machined surface roughface roughness gained by ultrasonic grinding (R_a=5.146 μm) is larger than that gained by the mechanical grinding (R_a=5.078 μm).

3.4 Ground surface topography

Abrasive machining is a process of micro-edge cutting, and the grinding surface topography reflects the relative movement track of the abrasive moving on the surface of specimen, the tiny plastic deformation and the brittle fracture remained on the machined surface after the abrasive machining.

The main purpose of this experiment is that grinding integral wheel on the Al_2O_3 ceramics with the Numerical Control contour evolution ultrasonic grinding method, as mentioned above. As in the process of grinding integral wheel, the direction of the main feed motion f_z is parallel to the direction of the ultrasonic vibration, and the machined surface topography gained in that vibration mode is observed in this paper.

From the topography observed through SEM, the machined surface of Al_2O_3 ceramics obtained by the ultrasonic grinding is smoother than that obtained by the common mechanical grinding after the sliding effect of the abrasives. From the images magnified 150 times shown in Fig.6 (a) and (b), it can be clearly seen that fewer scratch appears on the surface obtained by ultrasonic grinding, while more scratches emerge on the mechanical ground surface. And slight dilapidation and pits emerge on the ultrasonic ground surface, while more pits emerge on the mechanical grinding surface, and the size of the pits is larger correspondingly, even extensive cracks appear on the machined surface. Fig.6 (c) and (d) show the SEM photographs taken at the same magnification. From the photographs the existence of uncountable tiny scratches and plastic flow like metal cutting can be identified easily in the bottom of the grooves formed by ultrasonic grinding, and the grinding trace is smoother than the trace formed by mechanical grinding. There is no evident plastic deformation and splinter shaped microstructures of the ceramics distribute in the outside of the grooves.



Experimental conditions are the same as those in Fig.4, except V_s=4.058 m/s

Fig.6 Surface topographies of creep feed grinding with/without ultrasonic vibration

4 Discussions

When the direction of ultrasonic vibration is normal to the direction of creep feed, the ultrasonic vibration acts on the sensitive direction of machining. Because the amplitude of the ultrasonic vibration is small, while the grinding depth is large relatively, the abrasive particles can't break away from the machining surface in the process of creep feed ultrasonic grinding, and the abrasive particles strike or impact on the surface of the specimen, which leads to the microcracks on the surface and the relatively poor surface roughness. While the process of the mechanical grinding is the process composed of plowing, gliding and rubbing, the machined surface is smoother.

When the direction of ultrasonic vibration is parallel to the direction of the creep feed, the ultrasonic vibration acts on the insensitive direction of machining. Because the ultrasonic vibration velocity is far faster than the creep feed-rate of the machine tool, the microcracks formed by innumerable abrasive particles contacting with the material surface do not have time to spread and meet the microcracks brought by the new seams, which leads to the cutting scraps flaking off from the parent material. So the discontinuous seams formed by ultrasonic grinding are more uniform, and the cutting scraps flake as micropowder, the pits are smaller and shallower, which results in the better machined surface quality.

When the rotational speed of the grinding wheel increases, the contacting time between the abrasive particles and the surface of the specimen increases proportionally, which equals to increase the time of material finishing. So increasing the rotational speed of the grinding wheel is propitious to improve the machined surface quality, whether ultrasonic vibration is applied or not. While when the grinding speed is higher than the critical grinding speed, the contact between the abrasives and the specimen maintains, so the effect of ultrasonic vibration on the ground surface quality will decrease, and even disappear as the discontinuous grinding characteristic is changed in the process of ultrasonic grinding.

When the compounded feed method is applied, which is equivalent to exerting a low frequency vibration on the specimen normal to the direction of the main feed motion of the grinding wheel, and the interleaving reticular seams are formed on the machined surface, so the grinding seams are homogenized, and the ground surface quality is improved.

5 Feasibility Experiment of Creep Feed Ultrasonic Grinding Blade Surface

Reviewing from the above experimental results, it's hopeful to realize the creep feed ultrasonic grinding ceramic blade surface when selecting adaptable grinding parameters and the direction of the main feed motion is parallel to the ultrasonic vibration. In the later primary experiment of ultrasonic grinding the blade surface on the Al_2O_3 ceramics with thickness 4 mm, the simple blade surface (shown in Fig.7) is achieved. The selecting machining parameters are as follows: the diameter of the electroplated diamond wheel is 3 mm with the grain size #240 and concentration 75%; the rotational speed of the grinding wheel is 6 000 r/min; the given feed rate f_z of the worktable along z axis is 0.1 mm/min (based on the profile of the blades, selecting the feed rate of f_x is 0.086 mm/min, f_y is 0.006 mm/min and the rotational speed C_{w} is 0.3(°)/min); the vibration frequency f is 19.96 kHz, the amplitude of ultrasonic vibration A is about 5 μm, and the direction of vibration is parallel to the direction of the main grinding feed motion f_z.

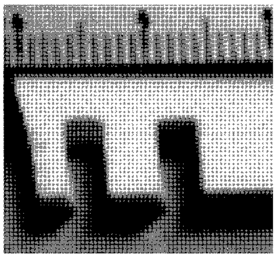


Fig.7 Slots between the blades obtained by ultrasonic grinding Al_2O_3 ceramics

6 Conclusions

(1) The effects of the grinding parameters on the ground surface roughness in the process of creep feed ultrasonic grinding ceramics are the same as those in the process of creep feed mechanical grinding. The deeper the grinding depth and the faster the grinding feed rate, the larger the value of the ground surface roughness. And the greater the rotational speed of the grinding wheel, the smaller the value of the ground surface roughness.

(2) The value of the ground surface roughness may be decreased when the compound feed mode is adopted.

(3) The value of the ground surface roughness obtained by creep feed ultrasonic grinding is always larger than that of creep feed mechanical grinding when the direction of ultrasonic vibration is normal

to the direction of creep feed. Compared to the mechanical grinding, the ultrasonic grinding may degrease the value of the machined surface roughness slightly and cracks and pits on the machined surface are fewer relatively when the direction of ultrasonic vibration is parallel to the direction of creep feed and the grinding speed is lower than the critical grinding speed.

(4) It's feasible to Numerical Control contour evolution creep feed ultrasonic grind ceramic blade surface when selecting adaptable grinding parameters and grinding method.

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