Research on the effect of ultrasonic vibration on the surface quality of ZTM ceramic material grinding

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Abstract. In this study, the effect of ultrasonic vibration on the surface quality of ZTM ceramic material grinding was carried out. The surface roughness characteristics of ZTM ceramics obtained by ultrasonic grinding and ordinary processing were compared, and the effects of abrasive grain size, table speed, grinding wheel speed, grinding depth and ultrasonic grinding processing methods on the surface quality of ceramic materials were studied. The linear speed of the grinding wheel and the grinding depth have close effects on the grinding surface roughness of ZTM ceramic materials. Ultrasonic grinding has a positive effect on the surface of ZTM ceramic processing, but it needs to be processed with a lower particle size grinding wheel to obtain a better improvement effect.

1. Introduction

Mullite ceramics have low fracture toughness (about 2 MPa.m⁻¹/₂) at room temperature and are prone to cracks and failure. This shortcoming limits its application in advanced structural ceramics. By adding ZrO₂ particles to improve the room temperature performance of mullite through the phase change toughening mechanism, zirconia toughened mullite ceramic (ZTM) materials are obtained [1,2,3].

At present, ZTM ceramic materials have been applied to heat-resistant and wear-resistant components such as the bottom plate of the cylinder head of the adiabatic engine, the top of the piston of the engine, the conveyor belt of the tunnel kiln, and the cylinder liner of the oil drilling mud pump [4]. Obtaining qualified dimensional tolerances and surface quality is the key to engineering ceramic materials processing technology. The processing surface quality of ceramic materials is more important. If there are scratches, damages and cracks on the ceramics surface after processing, it will lead to a decrease in the strength of the materials [5]. For precision parts with matching accuracy requirements, the quality of the final processed surface is more important in use. Taking the application of ceramic materials in the engine block as an example, if the surface quality is poor, surface wear will occur. The ceramic materials will cut the metal parts that match it or the surface contour peaks between the ceramic materials will collide with each other, which will eventually cause the parts to match. If the size exceeds the tolerance range, the matching accuracy will decrease, thereby increasing fuel consumption [6].

In order to improve the processing quality and efficiency of engineering ceramics, many scholars have done pioneering work. Among them, the use of ultrasonic grinding as a high-efficiency plastic removal method for ceramic materials has achieved remarkable results. Ultrasonic grinding uses a
magnetic hysteresis transducer to vibrate the rotating grinding wheel with axial ultrasonic vibration, and uses the grinding action of the grinding wheel and the impact, cavitation, and cracking effects generated by the ultrasonic vibration to remove materials and complete the surface processing. Cavitation and cracking caused by high-frequency ultrasonic vibration can effectively prevent the grinding wheel from clogging, realize the self-sharpening of the grinding wheel, and improve the processing efficiency [7,8,9,10].

This paper compares the surface roughness characteristics of ZTM ceramics obtained by ultrasonic grinding processing and ordinary processing methods, and studies the influence of abrasive grain size, table speed, grinding wheel speed, grinding depth and ultrasonic grinding processing methods on the surface quality of ceramic materials.

2. Test conditions

2.1 Specimen performance parameters
The performance parameters of the test materials are as follows: ZTM ceramic materials sintered by hot pressing, the volume content of ZrO2 is 15Vol%, and the specification R=60mm. The measured mechanical properties are as follows: Vickers hardness is 7.9GPa, fracture toughness is 4.1MPa.m1/2, density is 3.49g/cm3, and bending strength is 306MPa. The original surface roughness value of the ZTM ceramic test block after sintering was measured to be 0.73um.

2.2 Processing conditions
The HZ-63 type surface grinder was used to carry out the ZTM ultrasonic grinding test. In the test, an ultrasonic generator was used to apply ultrasonic vibration in the axial direction of the grinding wheel. The test device of the ultrasonic grinding system is shown in Figure 1. The test parameters are shown in Table 1.

2.3 Processing conditions
The Taylor Hobson-6 surface roughness meter was used to test the roughness, and the SU5000 scanning electron microscope was used to observe the microstructure of the sample.

3. Experimental results and discussion

3.1 The effect of grinding depth on surface roughness
The effect of grinding depth on surface roughness is shown in Figure 2 and Figure 3. It can be seen that in the ordinary grinding and ultrasonic grinding process, as the grinding depth increases, the surface roughness value will first decrease and then continue to increase. The increase in surface roughness means that brittle fracture mechanism is the main material removal method. The greater the grinding depth, the greater the grinding force, the greater the proportion of brittle fracture removal
methods, and the higher the grinding depth, the lower the surface quality. At the same time, the large cutting force will reduce the life of the grinding wheel and accelerate the failure of abrasive particles.

Table 1. Test and material parameters.

|                  | HZ-63 surface grinder                  |
|------------------|----------------------------------------|
| Grinder          | HZ-63 surface grinder                  |
| Ultrasonic vibration system | Ultrasonic generator ZJS-100 |
| Vibration amplitude: 10μm | Frequency: 20kHz |
| Grinding wheel   | material quality: CBN                  |
| Binder: Resin    | Concentration: 100%                   |
| Grain diameter: W10 W50 |                                      |
| Grinding conditions | Grinding wheel speed (m/s): 15, 22, 35 |
| Grinding depth (μm): 2, 4, 6, 8, 10 | Feed speed (m/s): 0.15, 0.2, 0.25, 0.30 |

3.2 The influence of grinding wheel linear speed on surface roughness

The influence of the linear speed of the grinding wheel on the surface roughness is shown in Figure 4 and Figure 5. It can be seen from the figure that in the process of ordinary grinding and ultrasonic grinding, the rough surface quality of the ceramic surface is obviously improved by using a high grinding wheel speed. The reasons are as follows: ① When the grinding wheel speed increases, the number of contacts between the grinding wheel and the workpiece per unit time increased, the friction and polishing effect on the surface of the workpiece is enhanced. ② When the linear speed of the grinding wheel is increased, the grinding force will be reduced, to a certain extent, the proportion of brittle fracture removal can be reduced, and the service life of the grinding wheel will also increase. The normal grinding time of the abrasive particles of the grinding wheel will be longer, thereby increasing the friction polishing time with the surface of the workpiece. ③ When the linear speed of the grinding wheel increases, the temperature of the grinding zone will increase significantly. Under the action of local high temperature, the fracture toughness of ceramic materials will increase, and the hardness will have a tendency to soften. At the same time, the ceramic may undergo plastic deformation under the extrusion of the grinding wheel, which further improves the surface quality.
3.3 The influence of table speed on surface roughness

The effect of grinding depth on surface roughness is shown in Figure 6 and Figure 7. In the two grinding methods, the table speed increases, and the surface roughness value increases slightly. The overall effect is lower than the grinding depth and the linear speed of the grinding wheel. The speed of the worktable has a slightly greater impact on ordinary grinding than that of ultrasonic grinding, which is caused by the increase in the speed of the worktable, which reduces the effective number of abrasive particles of the grinding wheel. It is also proved that ultrasonic grinding can equivalently increase the effective number of abrasive particles of the grinding wheel.

3.4 The influence of grinding wheel particle size on surface roughness

The particle size of the grinding wheel has a greater impact on the surface quality of ceramic processing. Under the same conditions, the surface quality of the ceramics processed by the grinding wheel with a particle size of W10 is better than that of the grinding wheel with a particle size of W50.

In the grinding depth effect experiment, when other conditions are the same. Comparing the surface quality of W10 and W50 grit grinding wheels, under ordinary grinding conditions, the surface quality of W10 grit grinding wheels is about 0.07-0.10um better than that of W50 grit grinding wheels.

In the experiment of grinding wheel linear velocity, when other conditions are the same. Comparing the surface quality of W10 and W50 grit wheels after processing, under ordinary grinding conditions, the surface quality of W10 grit wheels is about 0.08-0.10um better than that of W50 grit wheels.

In the workbench speed influence experiment, when other conditions are the same. Comparing the surface quality of W10 and W50 grit grinding wheels, under ordinary grinding conditions, the surface quality of W10 grit grinding wheels is about 0.06-0.09um better than that of W50 grit grinding wheels.
3.5 The effect of ultrasonic grinding on surface roughness

Ultrasonic grinding has a very positive effect on the improvement of the surface quality of ceramic processing. Under the same conditions, the surface quality of ceramics processed by ultrasonic grinding is better than that of ordinary grinding. Under the action of ultrasonic longitudinal vibration, the diamond grinding wheel rubs the peak of surface roughness many times, reduces the peak of surface roughness, and greatly improves the processing accuracy and the surface processing quality of the workpiece. Due to the application of high-frequency vibration, the surface of the diamond grinding wheel is not easily blocked by the grinding debris, the sharpness of the abrasive is maintained, the grinding efficiency is improved, and the cumulative grinding distance is increased.

In the grinding depth effect experiment, when the grinding wheel particle size is W10, the surface quality of the ceramic processed by ultrasonic grinding is improved by about 0.03-0.11um compared with the surface quality of the ceramic after ordinary grinding; when the particle size of the grinding wheel is W50, The surface quality of the ceramics processed by ultrasonic grinding is improved by about 0.02-0.05um compared with the surface quality of the ceramics processed by ordinary grinding. Under the conditions of ultrasonic grinding, the surface quality of the W10 grit grinding wheel is about 0.08-0.11um better than that of the W50 grit grinding wheel.

In the experiment on the influence of the linear speed of the grinding wheel, when the grinding wheel particle size is W10, the surface quality of the ceramic processed by ultrasonic grinding is improved by about 0.03-0.06um compared with the surface quality of the ceramic after ordinary grinding; when the particle size of the grinding wheel is W50, The surface quality of ceramics processed by ultrasonic grinding is improved by about 0.02-0.04um compared with the surface quality of ceramics processed by ordinary grinding. Under ultrasonic grinding processing conditions, the surface quality of the ceramic surface processed by the W10 grit grinding wheel is about 0.09-0.11um better than the ceramic surface processed by the W50 grit grinding wheel.

In the experiment on the influence of table speed, when the grinding wheel particle size is W10, the surface quality of the ceramic processed by ultrasonic grinding is improved by about 0.04-0.05um compared with the surface quality of the ceramic after ordinary grinding; when the particle size of the grinding wheel is W50, the surface quality of the ceramic is improved by about 0.04-0.05um. The surface quality of ceramics processed by ultrasonic grinding is improved by about 0.03-0.05um compared with the surface quality of ceramics processed by ordinary grinding. Under ultrasonic grinding processing conditions, the surface quality of the ceramic surface processed by the W10 grit grinding wheel is about 0.07-0.08um better than the ceramic surface processed by the W50 grit grinding wheel.

3.6 The influence of ultrasonic grinding on surface roughness

The grinding surface morphology of ZTM ceramic material is shown in Figure 8. From Figure 8(a), the surface texture of the ultrasonic vibration processing is refined, the groove depth is uniform, and the surface damage caused by processing is less, which shows that the main mechanism of material removal is plastic removal. It can be seen in Fig. 8(b) that the marks of abrasive grains can be clearly observed on the ordinary grinding surface, and there is a small amount of broken along the edge of the groove. It can be seen in Fig. 8(c) that the grinding grooves are shallower and more evenly distributed, and there are a lot of fractures along the edges of the grooves. This indicates that the main mechanism of material removal is brittle fracture removal. Under the action of ultrasonic vibration, the grain size of the grinding wheel is large. To a certain extent, increase the proportion of brittle fracture removal methods. It can be seen in Fig. 8(d) that the scratched groove on the machined surface is deeper, the cutting depth is uneven, and there are more breakages along the edge of the groove, compared to 8(c).
Figures 8(a-d) SEM image of machined surface 
(a) Ultrasonic grinding, Vs=22m/s, Vw=0.2m/s, ap=4μm, W10. 
(b) Ordinary grinding, Vs=22m/s, Vw=0.2m/s, ap=4μm, W10. 
(c) Ultrasonic grinding, Vs=22m/s, Vw=0.2m/s, ap=4μm, W50. 
(d) Ordinary grinding, Vs=22m/s, Vw=0.2m/s, ap=4μm, W50)

4. Conclusion
1. The particle size of the grinding wheel is W10. Under the same other conditions, the surface quality of the ceramic processed by ultrasonic grinding is improved by 0.03-0.11um compared with the surface quality of the ceramic processed by ordinary grinding. The particle size of the grinding wheel is W50. Under the same other conditions, the surface quality of the ceramic processed by ultrasonic grinding is improved by 0.02-0.05um compared with the surface quality of the ceramic processed by ordinary grinding. Corresponding to the same other conditions, under the ultrasonic grinding processing conditions, the ceramic surface processed by the W10 grit grinding wheel is improved by 0.07-0.11um compared with the ceramic surface processed by the W50 grit grinding wheel.

2. Ultrasonic vibration has a very positive effect on the improvement of the surface quality of ZTM ceramic material grinding. Under the ultrasonic vibration grinding, the ZTM ceramic surface is better improved. However, it must be matched with a lower particle size of the grinding wheel to obtain a better surface quality. Larger grinding wheel particle size under the action of ultrasonic vibration, although the surface roughness is reduced, but at the same time will increase the proportion of brittle fracture.

3. Grinding wheel linear speed and grinding depth have close influence on the grinding surface roughness of ZTM ceramic materials. Indirectly proves that the size of the grinding force can determine the quality of the ceramic processing surface. The speed of the worktable has little effect on the surface roughness of ceramic processing.

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References
[1] W. Wang, H. Li, Y. Guo, et al., Mullite whiskers prepared by molten salt method using Si powders, J. Adv. Ceram. 1 (2012) 283–289.
[2] S. Prusty, D.K. Mishra, B.K. Mohapatra, et al., Preparation of fused zirconia/mullite aggregates from sillimanite, zircon, and alumina mixtures via plasma, J. Am. Ceram. Soc. 95 (2012) 530–537.

[3] J. Zhong, J. Zhao, S. Liang, et al., Synthesis of spherical (30 nm) and rod-like (200 nm) zirconia core-reinforced mullite nanocomposites, Ceram. Int. 39 (2013) 4163–4170.

[4] Yu A B, Tan Y F, Xu Y S, et al. Wear resistance analysis of toughened mullite ceramic surface[J]. Diamond and Abrasive Engineering, 2003(01): 48-50.

[5] Jiang S Q. Research on the crack propagation and processing mechanism of ceramic materials under pre-compression [D]. Xiangtan University, 2012.

[6] Zhang J Y, Zhou X J. The application of ceramic materials in automobiles [J]. Automobile Technology and Materials, 2005, 000(008): 4-7.

[7] Gao G F. Study on elliptical vibration dressing technology and grinding performance of diamond grinding wheel[D]. Tongji University, 2008.

[8] Zhang N, Wei X, Wang Y C, et al. Experimental study on grinding force of ultrasonic vibration grinding of engineering ceramics[J]. Modular Machine Tool and Automatic Processing Technology, 2019, No.539(01):28-30.

[9] LI Z C, JIAO Y, DEINES T W, et al. Rotary ultrasonic machining of ceramic matrix composites: Feasibility study and designed experiments [J]. International Journal of Machine Tools and Manufacture, 2019, 54(12): 138-144.