Study on surface roughness of zirconia ceramics in high efficient and precision grinding process

Kechong Wang¹, Songhua Li¹,²,³ and Jian Sun¹

¹ School of Mechanical Engineering, Shenyang Jianzhu University, Shenyang, 110168, China; ²National-Local Joint Engineering Laboratory of NC Machining Equipment and Technology of High-Grade Stone, Shenyang Jianzhu University, Shenyang, 110168, China
³ Email: rick_li2000@163.com

Abstract. In order to solve the problem that the surface roughness of engineering ceramics is difficult to control, this paper studied the influencing factors of surface roughness of zirconia ceramic grinding. The effects of grinding depth, grinding wheel speed and workpiece feed rate on surface roughness were analyzed by the orthogonal experiments of zirconia ceramic grinding. On this basis, single factor experiments were carried out respectively, and the optimal combination of process parameters was analyzed. In addition, an empirical formula of surface roughness for the grinding of zirconia ceramics was established based on the experimental results. The results showed that the grinding depth had a great influence on the surface roughness, the grinding wheel speed effect was secondary, and the effect of the workpiece feed rate on the surface roughness was not very obvious. Compared with the measured value, the maximum relative error of the predicted value was less than 5%, which indicated that the empirical formula had a better prediction effect and provided a theoretical basis for reasonable selection of grinding parameters in actual processing.

1. Introduction

With the introduction of the “Made in China 2025” program, the demand for high-performance materials in various fields of industry is increasing day by day. Engineering ceramics have been widely used in aerospace, instrumentation, automotive manufacturing, petrochemical and biological medicine and other fields due to their high hardness, high strength, high heat resistance, high corrosion resistance and many other excellent properties [1]. However, engineering ceramics have high hardness and great brittleness, it is a typically difficult material to be processed. Therefore, it is of great significance for the application and further development of engineering ceramics to seek suitable processing methods [2].

At present, surface roughness is still one of the main parameters to evaluate the surface quality of workpiece [3]. Domestic and foreign scholars have done a lot of research on the grinding process of engineering ceramic materials, but there are few researches on the surface roughness of engineering ceramic grinding[4-7]. Xie et al. [8] started from the high-speed deep grinding mechanism of engineering ceramics and established corresponding mathematical models. Their research verified the accuracy of the models through experiments. Kuzin et al. [9] found the relationship between conditions of diamond grinding and the characteristic morphology of the surface of ground oxide-
ceramic specimens, and revealed that the type of these morphologies has a great effect on the tribological behavior of these specimens. Wu et al. [10] proposed a new surface roughness model for brittle materials based on a series of experiments on grinding of Silicon Carbide. Their results show that the model predictions have a good match with the experimental results.

In this paper, the orthogonal experimental method is used to conduct experiments. This method is based on the “orthogonal design array”, it can not only reduce the workload, but also ensure the reliability of the experiment, and can effectively save the experimental cost[11-12]. Through a series of zirconia ceramic grinding experiments are conducted, the influence of grinding parameters on the surface roughness of the machined surface is studied, which has important guiding significance for optimizing the processing parameters of engineering ceramic grinding and reasonable control of the surface quality.

2. Experimental work

2.1. Experimental materials and conditions
In the process of grinding experiments, the ceramic specimens are workblanks of zirconia ceramic, which are provided by Shanghai Institute of Ceramics of the Chinese Academy of Sciences. The specimens have dimensions of 20 mm × 20 mm × 15 mm. The main mechanical properties of zirconia ceramics used for the experiment are shown as Table 1.

| Density [g·cm⁻³] | Elasticity modulus [GPa] | Poisson ratio | Fracture toughness [MPa·m¹⁄₂] | Hardness [HRC] | Bending strength [MPa] |
|------------------|--------------------------|--------------|-------------------------------|---------------|----------------------|
| 5.88             | 195                      | 0.30         | 10.50                         | 78            | 750                  |

A resin bonded diamond grinding wheel is used in this experiment. The specifications of resin bonded diamond grinding wheel are listed in Table 2. All experiments are conducted under wet condition that a 3.8% solution of water-based cooling of fluid is applied. The flow rate of grinding fluid is 80 L/min in all experiment.

| Outer diameter [mm] | Inner diameter [mm] | Thickness [mm] | Grain size | Concentration [%] | Bond  |
|---------------------|---------------------|----------------|------------|-------------------|-------|
| 300                 | 127                 | 20             | 170⁵/200⁵  | 100               | Resin |

2.2. Experimental design
In this paper, the orthogonal experimental method is used to conduct experiments by a three-factor and four-level \( L_{16}(4^3) \) orthogonal table. The orthogonal factors and levels are shown in Table 3. The single-stroke cut grinding is used in the experiment, and the plane grinding under down grinding is selected as the grinding mode. The experiment studies the influence of machining parameters on the surface roughness during grinding.

In addition, in order to further optimize the grinding process parameters of zirconia ceramics, the influence of grinding depth, grinding wheel speed and workpiece feed rate on surface roughness of zirconia ceramic grinding are analyzed by using the single factor experiment based on the orthogonal experimental results.
### Table 3. Factors and levels of orthogonal experimental design

| Levels | Grinding wheel speed [m/s] | Grinding depth [mm] | Workpiece feed rate [mm·min⁻¹] |
|--------|---------------------------|---------------------|-------------------------------|
| 1      | 30                        | 0.005               | 1000                          |
| 2      | 35                        | 0.010               | 4000                          |
| 3      | 40                        | 0.015               | 7000                          |
| 4      | 45                        | 0.020               | 10000                         |

#### 2.3. Experimental apparatus and measuring instruments

The grinding experiment is performed on a high-precision ORBIT 36CNC forming grinder, the minimum resolution can reach 0.001 mm and the maximum grinding wheel speed can reach 70 m/s. Figure 1 shows the grinding experimental system. The grinding surface roughness is measured through the Surtron-ic25 Taylor Hobson roughness measuring instrument and measuring accuracy can reach 0.001 μm. Scanning electron microscope of S4800 produced by Hitachi is used to observe the surface morphology of processed ceramic specimens. It can adapt to the demand of high-resolution observation of different samples by EXB technology. The magnification factor of S4800 is ×20~×800000.

In addition, in order to reduce the error of the experimental results, five sets of data are measured for each specimen. After removing the maximum and minimum values, the final results of the experiment are represented by the average of the three sets of data.

![Grinding experiment system](image)

**Figure 1.** The grinding experiment system.

#### 3. Experimental results and analysis

**3.1. Analysis of the orthogonal experimental results**

According to the relevant properties of the orthogonal experiment, the experimental results are processed to obtain a surface roughness Ra response table, as shown in Table 4. The influence of grinding parameter on the surface roughness of zirconia ceramic grinding is shown in Figure 2.
Table 4. Response table for the surface roughness.

| Levels | Grinding wheel speed [m/s] | Grinding depth [mm] | Workpiece feed rate [mm·min⁻¹] |
|--------|---------------------------|---------------------|-------------------------------|
| 1      | 0.2037                    | 0.2072              | 0.2000                        |
| 2      | 0.2004                    | 0.1976              | 0.1983                        |
| 3      | 0.1963                    | 0.1915              | 0.2004                        |
| 4      | 0.1988                    | 0.2028              | 0.2006                        |
| Range  | 0.0074                    | 0.0157              | 0.0023                        |

The response tables for the surface roughness can accurately judge the effects of grinding parameters on surface roughness [13]. The results show that the major and minor order of the effect of grinding parameters on the surface roughness is the grinding depth, the grinding wheel speed and the workpiece feed rate.

Figure 2. Effect of grinding parameters on surface roughness.

3.2. Effect of the grinding depth on surface roughness

The result shows that the surface roughness generally decreases first and then increases with the increase of the grinding depth, the variations of the surface roughness with the grinding depth are as shown in Figure 3. When the grinding depth is 18 μm, the surface roughness is minimized. The reasons for this trend are as follows: with the increasing grinding depth, the grinding area increases, the dissipate heat condition of the grinding zone deteriorates, consequently a high temperature makes the workpiece soften seriously [14]. Thus the proportion of plastic removal of the ceramic material increases and it helps to reduce the surface roughness. With further enhancing of the grinding depth, the grinding depth exceeds the critical cutting depth of plastic and brittle removal. At the same time, the surface roughness is improved and it is disadvantageous to improving surface quality of the ceramic specimen.

Figure 3. Effect of the grinding depth on surface roughness.

Figure 4. Effect of the grinding wheel speed on surface roughness.
3.3. Effect of the grinding wheel speed on surface roughness

The effect of grinding wheel speed on the surface roughness of zirconia ceramic is shown in Figure 4. It can be seen from Figure 4 that the surface roughness decreases with the increase of the grinding wheel speed. When the grinding wheel speed is 43 m/s, the surface roughness is minimized. When the grinding wheel speed gets further increased, the surface roughness gets increased sharply and the surface quality becomes worse. The reason for this phenomenon is that the maximum undeformed cutting thickness of single grain decreases with the increase of the grinding wheel speed, the grinding force of a single grain decreases and specific grinding energy increases [15]. The proportion of plastic removal of the ceramic material increases and it helps to improve the surface quality. When the grinding wheel speed exceeds 43 m/s, the high-speed grinding increases the number of grinding chips, and the increase of grinding chips blocked between the convex abrasive leads to the passivation of the grinding wheel. As a result, the ability of grinding declines, and the grinding surface quality becomes worse. Consequently, suitable grinding wheel speed may be used in grinding process, which can not only reduce the grinding force and improve the surface quality, but also improve the removal rate of materials.

3.4. Effect of the workpiece feed rate on surface roughness

As is shown in Figure 5, the effect of the workpiece feed rate on the surface roughness is not very obvious. When the workpiece feed rate is low, with slow temperature rise, zirconia ceramics are mainly removed by plastic removal. It has increased from 1000 mm/min to 3000 mm/min, temperature rise leads to the increase of the proportion of plastic removal and the surface roughness decreases slightly. When the workpiece feed rate exceeds 3000 mm/min, the contact time between the grinding wheel and the workpiece is very short, the heat accumulation in the grinding area is less, the temperature has less influence on the ceramic material removal method [16]. Therefore, the surface roughness increases slightly.

![Figure 5. Effect of the workpiece feed rate on surface roughness.](image1)

![Figure 6. SEM image.](image2)

3.5. Selection of optimal grinding parameters

In the experiment of this paper, the roughness value is selected as a standard for testing the surface quality of zirconia ceramic grinding and the smaller the value of surface roughness, the better the surface quality of zirconia ceramic grinding. Therefore, when the optimal grinding parameters are selected, the parameters with small surface roughness should be selected as much as possible. The single factor experiment shows that when the grinding depth is 18 μm, the grinding wheel speed is 43 m/s and the workpiece feed rate is 3000 mm/min, the surface roughness value is the smallest, which is 0.1905 μm. SEM image of surface morphology of the tested specimen is shown in Figure 6. Therefore, recommended process parameters under the current experimental conditions included grinding depth of 17-19 μm, grinding wheel speed of 42-44 m/s and workpiece feed rate of 2500-3500 mm/min.
4. Establishment of roughness empirical formula

4.1. Empirical formula of grinding surface roughness

The investigation shows that there is a complex exponential relationship between the influencing factors of surface roughness and the surface roughness. After considering the grinding conditions in this paper, a simplified roughness expression is proposed as follows:

\[ R_a = C v_s a_p v_w \]  \hspace{1cm} (1)

where \( v_s \), \( a_p \) and \( v_w \) are the grinding wheel speed, the grinding depth, and the workpiece feed rate, respectively. \( k_1 \), \( k_2 \), \( k_3 \) and \( C \) are the parameters to be calculated respectively.

In order to simplify the calculation, the logarithm of the above expression is converted into a linear expression, which is denoted as \( y = k_0 + k_1 x_1 + k_2 x_2 + k_3 x_3 \). Hence, the following linear matrix equations can be established basing on the orthogonal experimental results as follows:

\[ Y = XK + \varepsilon \]

In the above equation, \( \varepsilon \) is the error, \( \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_{16} \end{bmatrix} = \begin{bmatrix} 1 & x_{1,1} & x_{1,2} & x_{1,3} & x_{1,4} \\ 1 & x_{2,1} & x_{2,2} & x_{2,3} & x_{2,4} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_{16,1} & x_{16,2} & x_{16,3} & x_{16,4} \end{bmatrix} \begin{bmatrix} k_0 \\ k_1 \\ k_2 \\ k_3 \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_{16} \end{bmatrix} \)

The parameters \( k_0 \), \( k_1 \), \( k_2 \) and \( k_3 \) are calculated by using the principle of least squares method. Therefore, the expression of \( K \) is as follows: \( K = (X'X)^{-1}X'Y \). After calculation, we can get \( K = \begin{bmatrix} -1.4922 & -0.0724 & -0.0293 & 0.0013 \end{bmatrix} \). Hence, the expression of grinding surface roughness is proposed as follows:

\[ R_a = 0.2249 v_s^{-0.0724} a_p^{-0.0293} v_w^{0.0013} \]  \hspace{1cm} (2)

4.2. Comparison of measured value with predicted value

Table 5. Compare roughness measurements with predicted values.

| No | Grinding wheel speed[m/s] | Grinding depth [mm] | Workpiece feed rate [mm·min⁻¹] | Measured value[μm] | Predicted value[μm] | relative error |
|----|--------------------------|---------------------|-------------------------------|-------------------|-------------------|---------------|
| 1  | 30                       | 0.005               | 1000                          | 0.2115            | 0.2303            | 2.02%         |
| 2  | 30                       | 0.010               | 4000                          | 0.2003            | 0.2196            | 1.54%         |
| 3  | 30                       | 0.015               | 7000                          | 0.1937            | 0.2226            | 3.83%         |
| 4  | 30                       | 0.020               | 10000                         | 0.2093            | 0.2284            | 4.69%         |
| 5  | 35                       | 0.005               | 4000                          | 0.2063            | 0.2238            | 0.50%         |
| 6  | 35                       | 0.010               | 7000                          | 0.1994            | 0.2149            | 0.93%         |
| 7  | 35                       | 0.015               | 10000                         | 0.1925            | 0.2180            | 3.40%         |
| 8  | 35                       | 0.020               | 1000                          | 0.2035            | 0.2248            | 3.32%         |
| 9  | 40                       | 0.005               | 7000                          | 0.2054            | 0.2223            | 0.99%         |
| 10 | 40                       | 0.010               | 10000                         | 0.1948            | 0.2117            | 2.37%         |
| 11 | 40                       | 0.015               | 1000                          | 0.1891            | 0.2176            | 3.90%         |
| 12 | 40                       | 0.020               | 4000                          | 0.1957            | 0.2197            | 0.27%         |
| 13 | 45                       | 0.005               | 10000                         | 0.2055            | 0.2305            | 1.82%         |
| 14 | 45                       | 0.010               | 1000                          | 0.1959            | 0.2179            | 0.64%         |
| 15 | 45                       | 0.015               | 4000                          | 0.1908            | 0.2210            | 2.32%         |
| 16 | 45                       | 0.020               | 7000                          | 0.2028            | 0.2279            | 4.51%         |
In order to verify the accuracy of the roughness expression, the orthogonal experimental data is substituted to the formula (2) to obtain the corresponding predicted value. The measured value is compared with the predicted value as shown in Table 5. By comparison, the minimum relative error between the predicted value and the measured value is 0.27%, and the maximum relative error is 4.69%. Therefore, the variation trend of roughness can be described accurately by the formula of this paper, which have better prediction performance. And the prediction accuracy of the formula can meet some requirement at engineering application.

5. Conclusions
During the zirconia ceramic grinding process, grinding surface roughness varies with grinding parameters. Meanwhile, the grinding depth has a great influence on the surface roughness, the grinding wheel speed is secondary, and the effect of the workpiece feed rate on the surface roughness is not very obvious. Under the current experimental conditions, recommended process parameters included grinding depth of 17-19 μm, grinding wheel speed of 42-44 m/s and workpiece feed rate of 2500-3500 mm/min. In addition, the empirical formula of grinding surface roughness has a better prediction effect and reasonable selection of grinding parameters can predict and control the surface roughness of zirconia ceramic grinding, which is of great significance for production and processing.

Acknowledgements
This work is supported by the National Natural Science Foundation of China (NO 51975388) and Liaoning Provincial Natural Science Foundation of China (NO 2019-MS-266). The author wish to record their gratitude for their generous supports.

References
[1] Zhang W R, Li L, Wang K 2016 J. Research status and development trend of advanced ceramic materials Advanced Materials Industry 01 2-8
[2] Lei L, Tian X L,Wang L, et al. 2016 J. Research progress of mechanical processing technology of engineering ceramics Journal of Ceramics 37 460-464
[3] M Baraheni, S Amin 2019 J. Predicting subsurface damage in silicon nitride ceramics subjected to rotary ultrasonic assisted face grinding Ceramics International 45 10086-10096
[4] Li Z P, Zhang F H, Luo X C, et al. 2019 J. Material removal mechanism of laser-assisted grinding of RB-SiC ceramics and process optimization Journal of the European Ceramic Society 39(4) 705-717
[5] Ding Z S, Jiang X H, Guo M X, et al. 2018 J. Investigation of the grinding temperature and energy partition during cylindrical grinding The International Journal of Advanced Manufacturing Technology 97(5-8) 1767-1778
[6] PSP Anand, N Arunachalam, L Vijayaraghavan 2017 J. Performance of diamond and silicon carbide wheels on grinding of bioceramic material under minimum quantity lubrication condition Journal of Manufacturing Science and Engineering 139(12) 1019-1029
[7] Feng J, Chen P, Ni J. 2013 J. Prediction of grinding force in micro-grinding of ceramic materials by cohesive zone-based finite element method International Journal of Advanced Manufacturing Technology 68(5-8) 1039-1053
[8] Xie G Z, Shang Z T, Sheng X M 2011 J. Grinding force modeling for high-speed deep grinding of engineering ceramics Journal of Mechanical Engineering 47(11) 169-176
[9] VV Kuzin, SY Fedorov, AE Seleznov 2016 J. Effect of conditions of diamond grinding on tribological behavior of alumina-based ceramics Trenie i Iznos 37(4) 475-481
[10] Wu C J, Li B Z, Liu Y, et al. 2017 J. Surface roughness modeling for grinding of silicon carbide ceramics considering co-existence of brittleness and ductility International Journal of Mechanical Sciences 43(01) 167-177
[11] Wan L L, Liu Z J, Deng Z H, et al. 2018 J. Simulation and experimental research on subsurface damage of silicon nitride grinding Ceramics International 44(7) 8290-8296
[12] E J Q, Han D D, Qiu A, et al. 2018 J. Orthogonal experimental design of liquid-cooling structure on the cooling effect of a liquid-cooled battery thermal management system Applied Thermal Engineering 132 508-520
[13] Li S H, Han T, Sun J, et al. 2018 J. Optimization experiment on HIPSN ceramic high efficient and precision grinding process Surface Technology 47 287-295
[14] Liu W, Deng Z H, Shang Y Y, et al. 2016 J. Single diamond grain grinding for silicon nitride Ordnance Material Science and Engineering 39 1-5
[15] Wu Y H, Wang W D, Li S H, et al. 2017 J. Experiments of surface roughness of zirconia ceramics under wet and dry grinding Journal of Shenyang Jianzhu University (Natural Science) 33 1080-1087
[16] Liu W, Deng Z H, Shang Y Y, et al. 2017 J. Effects of grinding parameters on surface quality in silicon nitride grinding Ceramics International 43 1571-1577