Optimization of Machining Parameters for Milling Zirconia Ceramics by Polycrystalline Diamond Tool

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Abstract: Zirconia ceramics are widely used in many fields because of their excellent physical and mechanical properties. However, there are some challenges to machine zirconia ceramics with high processing efficiency. In order to optimize parameters for milling zirconia ceramics by polycrystalline diamond tool, finite element method was used to simulate machining process based on Johnson-Cook constitutive model. The effects of spindle speed, feed rate, radial and axial cutting depth on cutting force, tool flank wear and material removal rate were investigated. The results of the simulation experiment were analyzed and optimized by the response surface method. The optimal parameter combination was obtained when the spindle speed, feed rate, radial and axial cutting depth were 8000 r/min, 90.65 mm/min, 0.10 mm and 1.37 mm, respectively. Under these conditions, the cutting force was 234.81 N, the tool flank wear was 33.40 µm when the milling length was 60 mm and the material removal rate was 44.65 mm³/min.

Keywords: zirconia ceramics; polycrystalline diamond tool; milling; finite element simulation

1. Introduction

Zirconia ceramics are characterized by high toughness, high bending strength, high wear resistance, excellent heat insulation, well corrosion resistance and biocompatibility [1–3], which have been expansively used in many areas such as aerospace, precision machinery and biomedicine [4–8]. High-efficiency processing for zirconia ceramics has become a research hotspot. The milling of zirconia ceramics can obtain complex three-dimensional structures and surface quality equivalent to grinding, which can make up for the limitations of existing processing technology to a certain extent [9]. However, it is different to machine zirconia ceramics because of their high toughness, high bending strength, high wear resistance and excellent heat insulation which cause severe tool wear and tipping, low surface quality and machining efficiency [10]. Polycrystalline diamond (PCD) tool has the advantages of high hardness, good thermal conductivity, low friction coefficient and low thermal expansion coefficient, which is an ideal tool for milling zirconia ceramics [11,12]. In recent years, a lot of research about surface quality, tool wear and material removal rate has been done when zirconia ceramics are machined by PCD tool [13–15].

Eleonora et al. [16] investigated the effects of cutting parameters on surface quality and tool wear cutting parameters on high speed hard cutting with PCD tool. The results showed that the material was mainly removed by combining ductile-brittle phases, and the tool wear was largely produced by workpiece material stuck to the tool. Bian et al. [17] studied the relationship between cutting parameters and brittle-tough critical cutting thickness during milling zirconia ceramics by using PCD tool. It was found that the appropriate increasing axial depth of cut can prevent the brittleness damage from affecting the machined surface and increase the material removal rate with the stabilization of the surface roughness within
During the milling of zirconia ceramic, the processing parameters should be accurately controlled because of the brittle fracture of zirconia ceramics, especially when the workpiece material is thin. Meanwhile, machining is accompanied by severe tool wear and low machining efficiency. It is very important to optimize the milling parameters of zirconia ceramics. In this paper, a finite element simulation model of PCD tool milling zirconia ceramics based on Johnson-Cook constitutive model was established. The milling experiments were designed with the central composite design method, and the simulation data was analyzed by regression analysis. The response surface method was used to analyze the effect of cutting parameters on cutting force, tool flank wear and material removal rate. The optimized parameter combination was obtained for the cutting force, tool flank wear, and material removal. The specific experiments were performed to verify simulation results.

2. Simulation Details

2.1. Constitutive Model

The Johnson-Cook constitutive equation was used to establish the constitutive model of zirconia ceramics milled by PCD tool. The model reflected the coupling effects of strain hardening, strain rate strengthening, and thermal softening during the cutting process. The expression is as follows [23]:

\[
\sigma = \left[ A + B (\varepsilon)^n \right] \left[ 1 + C \ln \left( \dot{\varepsilon} / \dot{\varepsilon}_0 \right) \right] \left[ 1 - \left( (T - T_r) / (T_m - T_r) \right)^m \right]
\]  

(1)

where, \(\sigma\) is equivalent flow stress (Mpa). \(A, B, C, n, m\) are the constants of the material under reference conditions, denoting yield stress (Mpa), strain hardening constant (Mpa), strengthening coefficient of strain rate, strain hardening coefficient and thermal softening coefficient, respectively. \(\varepsilon\) is equivalent plastic strain; \(\dot{\varepsilon}\) is equivalent plastic strain rate, and \(\dot{\varepsilon}_0\) is reference strain rate. \(T, T_r, T_m\) are maximum temperature of material, room temperature and melting temperature, respectively, usually measured in °C.

Johnson-Cook constitutive model parameters for zirconia ceramics are shown in Table 1.

| A/MPa | B/MPa  | C  | n  | m  | T_r/°C | T_m/°C |
|-------|--------|----|----|----|--------|--------|
| 930   | 310    | 0  | 0.6| 0.6| 25     | 1725   |

2.2. Three-Dimensional Finite Element Model

The physical properties of zirconia ceramics and PCD are shown in Table 2. The PCD tool is a second straight-tooth groove end mill with a diameter of 8 mm, helix angle and rake...
angle of 0°, and rear angle of 10°. The size of the zirconia ceramic is 100 × 30 × 20 mm³. The coefficient of friction is 0.3 incorporating a modified coulomb friction law with dry milling [24]. The zirconia ceramic and PCD are adopted an 8-node hexahedral element (C3D8RT) and 4-node tetrahedral unit (C3D4T), respectively. The milling schematic diagram is shown in Figure 1.

Table 2. Physical properties of workpiece and tool.

| Material         | Elastic Modulus E/(Pa) | Poisson’s Ratio μ | Thermal Conductivity κ/(W/m·K) | Heat Capacity c/(J/kg·K) | Density ρ/(kg/m³) |
|------------------|-----------------------|-------------------|--------------------------------|------------------------|------------------|
| Zirconia ceramics | 2.39 × 10¹¹           | 0.3               | 2.6                            | 400                    | 6050             |
| PCD              | 1.2 × 10¹²            | 0.2               | 1500                           | 471.5                  | 3520             |

![Figure 1. Milling schematic diagram.](image)

The material removal rate $Q$ is determined by the distance of milling and axial and radial depth per unit time. The $Q$ is calculated by the equation:

$$Q = v_f a_e a_p$$

(2)

where, $v_f$ is feed rate of tool feed rate, mm/s. $a_e$ and $a_p$ are the radial and axial depth of milling, mm, respectively.

During zirconia ceramic milled by PCD tool, the large cutting force will intensify the friction between the tool and the workpiece contact surface leading to severe damage on the tool surface, especially flank face. The rake and flank angle of the PCD tool used in this research is 0° and 10°, respectively. The schematic illustration of tool wear is shown in Figure 2. EOD is the shape of the tool. After the tool wear, the shape of the tool is EBCD as shown in Figure 2a,b shows the A-direction view of the tool. VB is the average wear of the flank face. In order to simplify the measurement of tool wear, tool wear in this research was replaced by $VB$ [25].
Response surface method was used to design the simulation experiment, which could obtain the influence of experiment parameter on results and its significance. Combined with engineering experience, four cutting parameters with five different levels of each were studied in the simulation experiment. The factors level of spindle speed (n), feed rate (v_f), radial depth of cut (a_e), and axial depth of cut (a_p) are shown in Table 3. The cutting force (F), tool flank wear (VB) and material removal rate (Q) were as the response performance indicator.

Table 3. Test factors level.

| No. | Control Factors | Level       |
|-----|-----------------|-------------|
| 1   | n/(r/min)       | 4000 5000 6000 7000 8000 |
| 2   | v_f/(mm/min)   | 20 40 60 80 100 |
| 3   | a_e/(mm)       | 0.03 0.06 0.09 0.12 0.15 |
| 4   | a_p/(mm)       | 0.6 1.2 1.8 2.4 3.0 |

There are four factors, according to central composite design, so the numbers of corner points are 16. The total number of experiments was 30.

3. Results and Discussion

3.1. Simulation Results

The simulation results of milling zirconia ceramics by PCD tool is shown in Figure 3. It can be seen that the stress mainly concentrated in the tip. For the simulation experiments, the simulation results of F, VB and Q under different n, v_f, a_e and a_p with the milling length of 60 mm are shown in Table 4.
Table 4. Simulation results of zirconia ceramic milling.

| No. | n/(r/min) | v/(mm/min) | a_e/(mm) | a_p/(mm) | F/(N) | VB/µm | Q/(mm³/min) |
|-----|-----------|------------|----------|----------|-------|--------|-------------|
| 1   | 5000      | 80         | 0.12     | 2.4      | 396.29| 107.31 | 23.04       |
| 2   | 4000      | 60         | 0.09     | 1.8      | 332.62| 2.70   | 9.72        |
| 3   | 5000      | 40         | 0.06     | 2.4      | 210.37| 102.73 | 5.76        |
| 4   | 6000      | 60         | 0.09     | 0.6      | 179.58| 8.25   | 3.24        |
| 5   | 7000      | 80         | 0.12     | 1.2      | 219.75| 79.39  | 11.52       |
| 6   | 5000      | 40         | 0.12     | 1.2      | 177.62| 81.92  | 5.76        |
| 7   | 6000      | 60         | 0.09     | 1.8      | 202.43| 89.44  | 3.24        |
| 8   | 7000      | 40         | 0.12     | 1.2      | 141.08| 116.97 | 5.76        |
| 9   | 8000      | 60         | 0.09     | 1.8      | 146.79| 86.31  | 9.72        |
| 10  | 7000      | 40         | 0.06     | 1.2      | 106.08| 79.43  | 2.88        |
| 11  | 6000      | 100        | 0.09     | 1.8      | 311.32| 86.18  | 16.2        |
| 12  | 7000      | 40         | 0.06     | 2.4      | 171.49| 142.52 | 5.76        |
| 13  | 7000      | 80         | 0.12     | 2.4      | 324.96| 143.52 | 23.04       |
| 14  | 6000      | 20         | 0.09     | 1.8      | 169.13| 117.32 | 3.24        |
| 15  | 7000      | 40         | 0.12     | 2.4      | 271.42| 174.30 | 11.52       |
| 16  | 7000      | 80         | 0.06     | 2.4      | 222.31| 108.54 | 11.52       |
| 17  | 6000      | 60         | 0.15     | 1.8      | 261.54| 167.51 | 16.2        |
| 18  | 6000      | 60         | 0.09     | 1.8      | 219.73| 86.45  | 9.72        |
| 19  | 6000      | 60         | 0.03     | 1.8      | 134.03| 64.75  | 3.24        |
| 20  | 6000      | 60         | 0.09     | 1.8      | 205.13| 106.89 | 9.72        |
| 21  | 7000      | 80         | 0.06     | 1.2      | 178.28| 27.84  | 5.76        |
| 22  | 6000      | 60         | 0.09     | 1.8      | 187.19| 90.34  | 9.72        |
| 23  | 5000      | 80         | 0.06     | 1.2      | 187.86| 54.75  | 5.76        |
| 24  | 5000      | 80         | 0.12     | 1.2      | 184.71| 76.46  | 11.52       |
| 25  | 6000      | 60         | 0.09     | 1.8      | 227.94| 82.34  | 9.72        |
| 26  | 6000      | 60         | 0.09     | 3.0      | 356.75| 175.33 | 16.2        |
| 27  | 5000      | 80         | 0.06     | 2.4      | 321.53| 52.85  | 11.52       |
| 28  | 6000      | 60         | 0.09     | 1.8      | 206.95| 84.90  | 9.72        |
| 29  | 5000      | 40         | 0.12     | 2.4      | 331.63| 116.29 | 11.52       |
| 30  | 5000      | 40         | 0.06     | 1.2      | 226.95| 58.30  | 2.88        |

3.2. Response Surface Analysis

The influences of spindle speed and feed rate on cutting force, tool flank wear and material removal rate are shown in Figure 4. It can be seen that the cutting force decreases significantly with the increase of spindle speed as shown in Figure 4a. The reason for this is that the increase of spindle speed causing the temperature of the processing area rise which reduces the strength and hardness of zirconia ceramics. However, the influences of spindle speed on tool flank wear and material removal rate are not obvious as shown in Figure 4b,c. The cutting force and material removal rate are increased with the increase of feed rate, especially material removal rate. Increasing the feed rate could increase the scan area of the tool in unit time results in an increase in material removal rate. The interaction between spindle speed and feed rate has the most significant impact on the cutting force, followed by tool flank wear, but no significant impact on the material removal rate.
The influences of radial and axial depth of cut on the cutting force, tool flank wear and material removal rate are shown in Figure 5. Radial depth of cut increase caused a slight increase of cutting force and tool flank wear, mainly because the cutting distance becomes longer and the cutting amount increases when the axial depth of the tool contact remains unchanged. The contact area between the tool and the workpiece increased with the increase of axial depth of cut [26]. Therefore, the cutting force and tool flank wear increased more than increasing the radial depth of cut as shown in Figure 5a–c shows that the material removal rate increased significantly regardless of whether the radial or axial depth of cut increased. The interaction between radial and axial depth of cut has a significant impact on the material removal rate, followed by cutting force and tool flank wear.

**Figure 4.** Response surface of spindle speed and feed rate on cutting force, tool flank wear and material removal rate. (a) Cutting force $F$, (b) Tool flank wear $VB$, (c) Material removal rate $Q$.

**Figure 5.** Response surface of radial depth of cut and axial depth of cut on cutting force, tool flank wear and material removal rate. (a) Cutting force $F$, (b) Tool flank wear $VB$, (c) Material removal rate $Q$.

### 3.3. Parameter Optimization

Multiple regression fitting was used to analyze the influence of $n$, $v_t$, $a_e$ and $a_p$ on $F$, $VB$ and $Q$. The second-order regression prediction models of $F$ (N), $VB$ (mm) and $Q$ (mm$^3$/min) are shown as follows:

\[
F = 906.66 - 0.13n - 4.31v_t - 2395.69a_e - 137.59a_p + 6.71 \times 10^{-6}n^2 + 0.02v_t^2 - 4187.85a_e^2 + 38.41a_p^2 + 3.48 \times 10^{-4}nv_t + 0.28n a_e - 0.01na_p + 0.92v_ta_e + 0.84v_ta_p + 1300.73a_ea_p
\]  \tag{3}

\[
VB = -224.65 + 0.12n - 0.48v_t - 1751.28a_e - 57.01a_p - 1.03 \times 10^{-5}n^2 + 0.01v_t^2 + 8481.71a_e^2 + 4.28a_p^2 - 2.69 \times 10^{-4}nv_t + 0.09na_e + 0.02na_p + 5.851v_ta_e - 0.13v_ta_p + 1.60a_ea_p
\]  \tag{4}

\[
Q = 3.5 \times 10^5 - 38.88n - 3888v_t - 2.59 \times 10^5a_e - 1.3 \times 10^5a_p + 0.32nv_t + 216na_e + 10.8na_p + 21600v_ta_e + 1080v_ta_p + 7.2 \times 10^5a_ea_p
\]  \tag{5}
Residual error was used to estimate whether the regression model is reasonable. Figure 6 shows the relation between predicted and simulated values of $F$, $VB$ and $Q$. It can be seen that all sample points are close to a straight line, and there are no out-of-range sample points. The correlation coefficient ($R^2$) of $F$, $VB$ and $Q$ is 0.9297, 0.9222 and 0.9501, respectively, which indicates that the second-order regression prediction models have less error and higher reliability [27,28].

![Figure 6](image_url)

**Figure 6.** The relation between predicted and simulated values. (a) Cutting force $F$, (b) Tool flank wear $VB$, (c) Material removal rate $Q$.

In order to further analyze the experimental factors on $F$, $VB$ and $Q$, the regression prediction models were analyzed by variance analysis. The results are shown in Table 5.

The $F$-value in Table 5 represents the ratio of the mean square between each group to the mean square within the group. If $\alpha$ is 0.05, the value of $F_{0.05(14,15)}$ is 2.42 according to the F distribution table. The $F$-value of $F$, $VB$ and $Q$ is 14.17, 12.70 and 743.85, respectively, which is more than 2.42 indicating the prediction model established significance. Simultaneously, the $p$-values of the model are less than 0.05, which also shows the model is effective [29].

The $p$-values of $n$, $v_t$, $a_e$ and $a_p$ in the $F$ regression model are less than 0.001, showing that the four experimental factors have extremely significant effects on the cutting force. The $p$-value of $a_e a_p$ is 0.0033 < 0.05 indicating $a_e$ and $a_p$ with significant interactive effects on $F$. The $F$-values of $n$, $v_t$, $a_e$ and $a_p$ are 34.56, 27.00, 26.54 and 80.76, respectively. According to the $F$-values, the influence of the four experimental factors on $F$ is $a_p > n > v_t > a_e$.

The $n$, $v_t$, $a_e$ and $a_p$ have extremely significant effects on the $VB$ because of the $p$-values of $n$, $a_e$ and $a_p$ in the $VB$ regression model less than 0.001. The $p$-value of $n a_p$ is 0.0301 < 0.05, showing that spindle speed and axial depth of cut have a significant interactive effect on the $VB$. According to the $F$-values, the influence of the four experimental factors on $VB$ is $a_p > a_e > n > v_t$.

The $p$-values of $v_t$, $a_e$ and $a_p$ in the $Q$ regression model are less than 0.0001, which indicates $v_t$, $a_e$ and $a_p$ have extremely significant effects on the material removal rate. The $F$-values of $n$, $v_t$, $a_e$ and $a_p$ are 1.042, 2308.5, 2308.5 and 2308.5, respectively. According to the size of the data, the influence of the four experimental factors on $Q$ is $v_t = a_e = a_p > n$.

In order to obtain multi-objective optimal machining parameters, the regression prediction models of $F$, $VB$ and $Q$ were considered comprehensively under the same weight. A set of optimal machining parameters with the smallest cutting force, the smallest tool flank wear, and the largest material removal rate were obtained: $8000$ r/min for $n$, 90.65 mm/min for $v_t$, 0.10 mm for $a_e$, and 1.37 mm for $a_p$. Under this condition, the $F$ is 234.81 N, the $VB$ is 33.40 $\mu$m, and the $Q$ is 44.65 mm$^3$/min under the milling length of 60 mm.
Table 5. Analysis of variance of regression prediction models.

| Source        | $F$       | VB        | Q         |
|---------------|-----------|-----------|-----------|
|               | Sum of Squares | df | Sum of Squares | df | Mean Square | F-Value | p-Value | Mean Square | F-Value | p-Value | Sum of Squares | df | Mean Square | F-Value | p-Value |
| Model         | 143,000   | 14 | 48,094.43    | 14 | 3435.32 | 12.70 | <0.0001 | 3435.32 | 12.70 | <0.0001 | 811.81 | 10 | 81.18 | 743.85 | <0.0001 |
| $n$           | 24,913.15 | 1  | 6309.58      | 1  | 6309.58 | 23.33 | 0.0002 | 6309.58 | 23.33 | 0.0002 | 0.00   | 1   | 0.00 | 1.04  | 1.0000 |
| $v_t$         | 19,461.52 | 1  | 3372.04      | 1  | 3372.04 | 12.47 | 0.0030 | 3372.04 | 12.47 | 0.0030 | 251.94 | 1   | 251.94 | 2308.50 | <0.0001 |
| $a_e$         | 19,131.47 | 1  | 9389.17      | 1  | 9389.17 | 34.71 | <0.0001 | 9389.17 | 34.71 | <0.0001 | 251.94 | 1   | 251.94 | 2308.50 | <0.0001 |
| $a_p$         | 58,214.49 | 1  | 20,849.44    | 1  | 20,849.44 | 77.08 | <0.0001 | 20,849.44 | 77.08 | <0.0001 | 251.94 | 1   | 251.94 | 2308.50 | <0.0001 |
| $n v_f$       | 775.76    | 1   | 462.90      | 1  | 462.90 | 1.71  | 0.2105 | 462.90 | 1.71  | 0.2105 |
| $n a_e$       | 1147.69   | 1   | 112.47      | 1  | 112.47 | 0.42  | 0.5288 | 112.47 | 0.42  | 0.5288 |
| $n a_p$       | 1184.91   | 1   | 1552.36     | 1  | 1552.36 | 5.74  | 0.0301 | 1552.36 | 5.74  | 0.0301 |
| $v_f a_e$     | 4.92      | 1   | 196.84      | 1  | 196.84 | 0.73  | 0.4070 | 196.84 | 0.73  | 0.4070 |
| $v_f a_p$     | 1626.31   | 1   | 40.01       | 1  | 40.01 | 0.15  | 0.7059 | 40.01 | 0.15  | 0.7059 |
| $a_e a_p$     | 8770.79   | 1   | 0.01        | 1  | 0.01 | 0.00  | 0.9945 | 0.01 | 0.00  | 0.9945 |
| $n^2$         | 1235.29   | 1   | 2897.50     | 1  | 2897.50 | 10.70 | 0.0052 | 2897.50 | 10.70 | 0.0052 |
| $v_f^2$       | 1283.61   | 1   | 445.42      | 1  | 445.42 | 1.65  | 0.2189 | 445.42 | 1.65  | 0.2189 |
| $a_e^2$       | 389.65    | 1   | 389.65      | 0.54 | 473.6 | 1598.29 | 1  | 1598.29 | 5.91  | 0.0281 |
| $a_p^2$       | 5243.15   | 1   | 5243.15     | 7.27 | 0.0166 | 65.03  | 1  | 65.03 | 0.24  | 0.6310 |
| Residual      | 10,813.15 | 15   | 720.88     | —  | —  | 4057.11 | 15 | 270.47 | —  | 2.07  |
| Lack of Fit   | 3676.14   | 10   | 367.61     | 4.86 | 0.0474 | 3676.14 | 10 | 367.61 | 4.82 | 0.0482 |
| Pure Error    | 1008.30   | 5    | 210.66     | —  | —  | 380.97  | 5  | 76.19 | —  | —  |
| Cor Total     | 153,800   | 29   | —  | —  | —  | 52,151.54 | 29 | —  | —  | —  |
3.4. Model Validation with Experiments

In order to verify the validity of the prediction models, the experiments of milling zirconia ceramics by PCD tool were carried out in vertical drilling and tapping center TC500R. The experiments were repeated three times under the conditions of the optimal combination of machining parameters to obtain an average value. The results are shown in Table 6. According to the results of three experiments, the average values of $F$, $VB$ and $Q$ are $208.08$ N, $29.24$ µm, and $41.87$ mm$^3$/min, respectively. Compared with the predicted results, the relative errors of $F$, $VB$ and $Q$ are $11.38\%$, $12.46\%$ and $6.23\%$, respectively, all less than $15\%$, which indicates that it is reasonable and feasible to use response surface method to optimize the machining parameters of milling zirconia ceramics by PCD tool.

|       | 1   | 2   | 3   | Average | Predicted Value |
|-------|-----|-----|-----|---------|-----------------|
| $F$(N) | 208.81 | 221.69 | 193.75 | 208.08  | 234.81          |
| $VB$(µm) | 29.67 | 30.84 | 27.22 | 29.24  | 33.40          |
| $Q$(mm$^3$/min) | 38.40 | 40.30 | 47.10 | 41.87  | 44.65          |

4. Conclusions

In this paper, we established a finite element model to simulated milling zirconia ceramics by PCD tool. The influence of $n$, $v_f$, $a_e$ and $a_p$ on $F$, $VB$ and $Q$ were studied. The response surface method was used to analyze and optimize the milling parameters. The second-order regression prediction models of $F$, $VB$ and $Q$ were established with the confidence level of each prediction model higher than $0.92$. The influence of experimental factors on $F$, $VB$ and $Q$ is $a_p > n > v_f > a_e$, $a_p > a_e > n > v_f$ and $v_f = a_e = a_p > n$, respectively. When the multi-objective optimal machining parameters with $F$, $VB$ and $Q$ were under the same weight, the optimal parameters of $n$, $v_f$, $a_e$ and $a_p$ are $8000$ r/min, $90.65$ mm/min, $0.10$ mm, and $1.37$ mm, respectively. Under this condition, $F$ was $234.81$ N, $VB$ was $33.40$ µm and $Q$ was $44.65$ mm$^3$/min, when the milling length was $60$ mm. Comparing the experimental and simulation results, the relative errors of $F$, $VB$ and $Q$ are $11.38$, $12.46$ and $6.23\%$, respectively. They are all smaller than $15\%$ indicating that it is reasonable and feasible to use the response surface method to optimize the machining parameters of milling zirconia ceramics by PCD tool.

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