Study of milling process basics for the biocompatible PEEK material

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Abstract

Polyetheretherketone (PEEK) material has attracted attentions and studies in the medical field due to its excellent properties suitable for orthopedic, dental, and implant applications. In order to acquire the needed geometrical accuracy and surface finish for individual customizations of components made of PEEK material, milling process basics for PEEK material have been studied in this paper. The influences of milling parameters on milling forces and surface roughness are discussed based on single-factor and orthogonal milling experiments. It shows that the effects of cutting parameters on cutting forces are basically in accordance with that in the classical metal cutting theory. But the effects of cutting parameters on the surface roughness are different. Also the significance sequences of the key milling parameters on milling forces and surface roughness are identified. Furthermore, a finite element simulation model to estimate the milling force is established and successfully evaluated for customized applications.

1. Introduction

PEEK material, a semi crystalline and thermoplastic polymer, has similar elastic modulus as bones, good biocompatibility, natural radiolucency, and stable chemical/sterilization resistance. Therefore, it has been taken as one of the promising materials used for orthopedic and dental materials [1, 2]. With further studies on endowing PEEK with improved bioactivity, PEEK material is believed to be the most suitable material for human bone implants such as spine fusions and joint replacements [1, 3, 4].

Izamshahet et al have determined the effect of cutter geometrical features for PEEK material machining by Taguchi method [5]. It turned out that the cutter geometrical features had significant effects on the machined surface roughness. Abdullah et al optimized the machining parameters (cutting speed, feed rate and depth of cut) for effective machining of PEEK implant material using carbide cutting tools [6]. Based on the analysis results of Response Surface Methodology (RSM), the optimal machining parameters for the minimum surface roughness values were obtained. Izamshah et al aimed to control the cutting force by optimizing the cutter geometries especially the rake, clearance and helix angles on machining of the PEEK material [7]. RSM approach was applied to design and analyze the optimal combinations of tool geometry features for PEEK material machining. Li et al have carried out experimental studies of water jet turning of carbon-fiber-reinforced PEEK material. Mainly the material removal rate and surface roughness have been analyzed [8]. Jogi et al have optimized the turning processes for PEEK material by using the Taguchi method taking the cutting forces and surface roughness into consideration [9]. Davim et al conducted a study on the mathematical modeling of the orthogonal cutting of the PEEK material and the PEEK composite material reinforced with 30% of carbon fiber (CF30) [10]. The influences of the reinforcement on the chip thickness ratio, chip deformation, friction angle, shear angle, normal stress and shear stress under prefixed cutting parameters have been evaluated.

A nanosized hydroxyapatite (HA) modification on PEEK using a novel spin coating technique was investigated in a rabbit model. Histomorphometric assessment showed higher bone-implant and bone area values for HA-PEEK, and the effect of the HA coating showed most prominent effect in the removal torque [11]. CF-PEEK composites were manufactured by 3D-printing using a novel FDM methodology and customized printer and were compared with their cast counterparts. The characterization of composite thermal properties
in the range 25 °C–300 °C revealed that 3D-printed CF-PEEK composites manifest 25%–30% lower thermal conductivity than cast composites [12]. Testing methods have been developed to compare the mechanical responses and failure behavior of PEEK thermoplastic polymer; under quasi-static, high strain rate tensile tests and fatigue loading [13]. Gallagher et al have the first investigation of the mechanical behaviour and failure mechanisms of PEEK-OPTIMA™ Ultra-Reinforced [14].

According to statistics, there are more than 3 million patients suffering from bone injury caused by orthopedic diseases, traffic accidents and safety accidents in production in China every year, but 98% of the patients suffering from bone defects in China have become the persons with limited function due to the lack of ideal artificial implants. At present, there are more than 15 million such patients. Therefore, the design and manufacture of personalized implants is very urgent [15]. However, according to literature surveys, there is a gap between the urgent requirements and the high-quality fabrication of the individual customizations of components made of PEEK material since the comprehensive studies considering both cutting forces and surface roughnesses for PEEK material by the milling process are very limited. Considering the fact that the milling process has high flexibility and high fabrication efficiency for customized human bone implants, especially under emergent situations, the milling process basics for PEEK material have been studied in this paper. The effects of milling parameters on both cutting forces and surface roughnesses have been studied according to single-factor and orthogonal milling experiments. Then, the finite element model for PEEK milling is created and evaluated by the experimental results.

### 2. Experiment preparation

#### 2.1. Workpiece material and cutting tool

Four-edge carbide end mills with the diameter of 5 mm are used. Main parameters of the cutters are shown in table 1. The workpiece used is a block PEEK material and the size is 50 × 30 × 20 mm. The mechanical properties of the workpiece material are shown in table 2 [16].

#### 2.2. Experiment equipment

The machine tool used for the experiments is a 3D printing and milling combined machine tool, as shown in figure 1. The maximum spindle speed is 24000 min⁻¹. The Kistler dynamometer 9257B is used for the milling
force measurement. The schematic diagram of milling force measuring system is shown in figure 2. A portable surface roughness tester (Model CS-3200) is used for the surface roughness measurements. Both cutting forces and surface roughnesses are measured five times, and the arithmetic mean values are calculated for the analyses.

3. Experimental design and results

The main purpose of the experiments is to obtain the influences of milling parameters on milling forces and surface roughnesses. The selected key process parameters are radial depth of cut $a_e$, axial depth of cut $a_p$, and feed engagement $f_z$. Firstly, the single-factor experiments are conducted to study the influence tendency of each process parameter on cutting forces and surface roughnesses. Consequently, the suitable parameter range of each parameter for the following orthogonal experiments is to be identified. Then, orthogonal experiments are designed and conducted. Through the results analyses of the orthogonal experiments, the influence degree and significance of each factor on milling forces and surface roughnesses are investigated.

3.1. Single-factor experiments

3.1.1. Single-factor experiment design

Before the milling experiment is carried out, the workpiece has been pre-milled to obtain a smooth top surface. The single-factor experiment is conducted for each key process parameter separately. The tool moving paths for the single-factor experiments are shown in figure 3.
Figure 3(a) shows the tool moving path for the radial depth of cut $a_e$. First of all, the cutter mills a groove along the x-axis direction (the width of the groove is equal to the tool diameter $D$, and the depth of the groove is equal to the axial depth of cut $a_p$). After groove milling is completed, the cutter feeds in the y-axis direction with radial depth of cut $a_e1$. Then, the cutter moves in the negative x-axis direction. After the cutting is completed, the cutter feeds 8 mm in the y-axis direction and repeats the previous paths for total five times with different radial depths of cut. Figure 3(b) shows the tool moving path of the axial depth of cut $a_p$, which is basically the same as that of $a_e$. The differences are that the radial depth of cut is fixed and the axial depth of cut is changing. Figure 3(c) shows the tool moving path of the feed engagement $f_z$, where both the radial depth of cut is fixed and the axial depth of cut are fixed and the feed engagement is changing.

The milling parameters selected for the three groups of single-factor experiments are shown in table 3, where the spindle speed is fixed at 15000 min$^{-1}$. All the experiments have been repeatedly conducted for three times and new cutters are used for each time.
3.1.2. Milling force

Milling forces data in axes X, Y, and Z under stable cutting conditions have been collected, noise processed, and averaged. Then, the resultant milling force is computed by equation (1).

\[ F = \sqrt{F_x^2 + F_y^2 + F_z^2} \]  

where, \( F \) is the resultant force, \( F_x \) is the milling force in \( x \)-axis direction, \( F_y \) is the milling force in \( y \)-axis direction, and \( F_z \) is the milling force in \( z \)-axis direction.

Experimental forces are shown in figure 4. Among the three milling force components, \( F_z \) is the smallest one and \( F_y \) is the largest one. The milling forces increase with the increase of cutting parameters \( a_e, a_p, f_z \). The results show that the cutting force tendency in PEEK material cutting is basically in accordance with that in the classical metal cutting theory \[17–19\].

From figure 4, the increase rate of cutting forces by each parameter has an obvious change. For example, as shown in figure 4(a), when the radial depth of cut \( a_e \) is smaller than 0.9 mm, the force increase rate remains almost constant. Then, the force increase rate changes and becomes larger after \( a_e \) is larger than 0.9 mm. Milling parameters corresponding to smaller cutting force increase rate are preferred for the coming orthogonal experiments. Therefore, the reasonable range for each parameter can be selected according to this result. From figure 4, the reasonable parameter ranges for \( a_e, a_p, \) and \( f_z \) are 0.3 to 0.9 mm, 0.3 to 1.3 mm, and 0.04 to 0.07 mm \( z^{-1} \), respectively.

3.1.3. Surface roughness

The surface roughness \( R_a \) under different cutting parameters has been collected and averaged for five-times measurements as shown in figure 5.
The surface roughnesses increase with the increase of cutting parameters $a_e$, $a_p$, and $f_z$. The effects of cutting parameters on surface roughness, from large to small, are the axial depth of cut, the radial depth of cut, and the feed engagement. This phenomenon in PEEK material cutting is different from that in the classical metal cutting theory, where the feed engagement has the largest effect on surface roughness \cite{20, 21}.

From figure 5, the increase rate of surface roughness by each parameter has an obvious change. For example, as shown in figure 5(a), when the radial depth of cut $a_e$ is smaller than 0.6 mm, the increase rate of the surface roughness remains almost constant. Then, the surface roughness increase rate changes and becomes larger after $a_e$ is larger than 0.6 mm. For the same reason as mentioned in the cutting force analyses, the reasonable parameter ranges for $a_e$, $a_p$, and $f_z$ are 0.3 to 0.6 mm, 0.3 to 1.3 mm, and 0.04 to 0.07 mm $z^{-1}$, respectively.

### 3.2. Orthogonal experiment

#### 3.2.1. Experiment design

Based on the results from single-factor experiments and Taguchi’s method, four levels are selected for each factor as shown in table 4. The $L_{16}$ orthogonal array is used to design the orthogonal experiments \cite{22, 23}.
3.2.2. Milling force

The resultant milling forces from the orthogonal experiment are shown in figure 6. It shows when $a_e = 0.5$ mm, $a_p = 1.1$ mm, $f_z = 0.06$ mm $z^{-1}$, the minimum milling force is achieved. Therefore, this is the optimal set of parameters for the milling force in PEEK milling applications.

Based on the analyses of variance (ANOVA), the results of the orthogonal experiments are processed. With a confidence level of 95%, table 5 shows the analytical results, where A is the radial depth of cut, B is the axial depth of cut $a_p$, and C is the feed engagement.

![Figure 7. The value of the surface roughness in the orthogonal experiment.](image)

According to the ANOVA, the milling parameters are found to be significant with a P-value of less than 0.05, which indicate that these parameters have significant influences. F-value is used as a secondary reference. Based
on the P-value and F-value in table 5, the significant factors for milling forces in the order from large to small are A, B, and C. Therefore, in order to improve the processing efficiency, the feed engagement can be reasonably increased in the actual PEEK machining.

3.2.3. Surface roughness
The surface roughnesses from the orthogonal experiments are shown in figure 7. It shows when \( a_e = 0.5 \text{ mm} \), \( a_p = 1.1 \text{ mm} \), \( f_z = 0.06 \text{ mm} \text{ z}^{-1} \), the minimum surface roughness is created. Therefore, this is the optimal set of parameters for the surface roughness, which is the same as that analyzed from the milling forces.

Based on the analyses of variance (ANOVA), the results of the orthogonal experiments are processed. With a confidence level of 95%, table 6 shows the analytical results. The significant factors for surface roughnesses in the order from large to small are B, C, and A, namely, \( a_p \) exerts the strongest influence, while \( f_z \) has a secondary influence, and \( a_e \) has the smallest influence on the surface roughness.

### 4. Prediction model
The above experimental results are universal for PEEK milling applications. But for different geometrical features in customizing various implants, the cutting forces are better to be estimated to avoid large deformations and consequently to assure the geometrical accuracies. Therefore, finite element simulation models are created and evaluated to form a basis for practical applications in customized implant fabrications.

| Table 5. The analyses of variance results of milling force. |
|---------------------------------|
| Source | Sum of Squares | DF | Mean Square | F-Value | P-Value | Remark |
|--------|----------------|----|-------------|---------|---------|--------|
| A      | 20.4844        | 3  | 6.8281      | 34.65   | 0.000   | significant |
| B      | 14.2298        | 3  | 4.7433      | 24.07   | 0.001   | significant |
| C      | 0.6283         | 3  | 0.2094      | 1.06    | 0.432   | not significant |
| Error  | 1.1822         | 6  | 0.1970      |         |         |         |
| Total  | 36.5247        | 15 |             |         |         |         |

| Table 6. The analysis of variance results of surface roughness. |
|---------------------------------|
| Source | Sum of Squares | DF | Mean Square | F-Value | P-Value | Remark |
|--------|----------------|----|-------------|---------|---------|--------|
| A      | 0.0094         | 3  | 0.0031      | 19.60   | 0.002   | significant |
| B      | 0.0729         | 3  | 0.0243      | 151.31  | 0.000   | significant |
| C      | 0.0197         | 3  | 0.0066      | 40.94   | 0.000   | significant |
| Error  | 0.0010         | 6  | 0.0002      |         |         |         |
| Total  | 0.1031         | 15 |             |         |         |         |

Figure 8. Finite element model.
4.1. Finite element model
Based on the finite element software Deform-3D, the milling model has been created for the simulation employing the classical Johnson-Cook constitutive material model. The three-dimensional model of the tool and workpiece has been created by the software Solidworks. The milling cutter remains the same as that for experiments. The size of workpiece is $3 \times 3 \times 3$ mm. The geometric model of the cutter has been simplified to improve the simulation speed according to literature [24]. The precutting preparation is conducted to the workpiece model and the assembled final finite element model is shown in figure 8.

The reasonable meshing can ensure the simulation quality and reduce the simulation time. The meshing of workpiece and cutter is shown in figure 9, where the tetrahedral mesh type is applied. The local grids are refined with the size of 1 $\mu$m for cutting edges and the cutting zone in the workpiece. It can simultaneously guarantee the simulation precision, shorten the remeshing time and improve simulation speed. Furthermore, the adaptive meshing method has been applied and the mesh size can be refined according to the real-time calculation requirements.

4.2. Simulation process
The same parameters in table 4 are selected for simulations. When radial depth of cut $a_e = 0.5$ mm, axial depth of cut $a_p = 1.1$ mm, and feed engagement $f_z = 0.06$ mm $z^{-1}$, the simulation process is shown in figure 10.

The milling forces in three directions X, Y, and Z with different milling parameters can be computed by data processing. For example, when $a_e = 0.5$ mm, $a_p = 1.1$ mm, and $f_z = 0.06$ mm $z^{-1}$, the milling forces in each direction X, Y, and Z are shown in figure 11.

4.3. Evaluation
The simulated forces are summarized and compared in table 7. From table 7, the absolute value of the relative errors between the simulated cutting forces values and the experimental ones are smaller than 6%. Considering the machine tool vibration, noise in the measurement process and tool wears, the simulation result can be considered as reliable. Therefore, this simulation model can be used to predict the milling force effectively.
Table 7: Milling forces and relative errors between the simulated values and the experimental ones.

| No. | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Simulated (N) | 5.6 | 6.6 | 6.7 | 7.0 | 6.1 | 7.5 | 8.6 | 9.3 | 6.2 | 9.6 | 8.9 | 9.7 | 8.2 | 9.5 | 10.4| 10.7 |
| Experimental (N) | 5.3 | 7.0 | 6.5 | 7.3 | 5.8 | 7.9 | 8.4 | 8.8 | 6.3 | 9.5 | 9.2 | 9.5 | 8.6 | 9.8 | 9.9 | 10.1 |
| Relative error (%) | 5.7 | -5.7| 3.1 | -4.1| 5.2 | -5.1| 2.4 | 5.7 | -1.6| 1.1 | -3.3| 2.1 | -4.7| -3.1| 5.1 | 5.9 |
4.4. Application

Since PEEK is a typical ductile material and the yield strength is far larger than the tensile strength as shown in table 2, the main concern in PEEK cutting is the workpiece’s deformation. The created finite element cutting model can be used to estimate cutting forces, which will be applied to judge the geometrical deformations by finite element analyses. As shown in figure 12, three thin-wall features are designed and their deformations are simulated by the cutting force relating to the optimized cutting parameters.

From figures 12(a) and (b), the workpiece has no obvious deformations. But deformations of the thin wall in figure 12(c) are obvious. According to the results of variance analysis of milling forces, the radial depth of cut $a_e$ has the greatest influence on the milling force. Therefore, for the third thin-wall feature, the milling force can be
reduced by reducing the radial depth of cut $a_e$, so as to reduce the deformation of the workpiece. The radial depth of cut $a_e$ is selected as 0.4 mm, and the other two parameters remain unchanged to simulate the third thin-wall feature. The simulation result is shown in figure 13, where there are no obvious deformations of the thin wall structure. Therefore, the workpiece deformation can be reduced by reasonably reducing the cutting parameters according to the finite element simulations.

The first thin-wall feature is milled, as shown in figure 14. The machined thin-wall is measured and no obvious deformations are found. It is consistent with the simulation result. Therefore, the simulation model can be used to guide the actual milling applications of the PEEK material.

5. Conclusion

Milling process basics have been studied for the PEEK material by milling experiments and finite element simulations. It shows that milling forces in three directions and the resultant force have a monotonous increase trend with the increase of three milling parameters. The radial depth of cut $a_e$ and axial depth of cut $a_p$ have significant influences on milling forces and feed engagement $f_z$ has no significant influences on milling forces, while radial depth of cut $a_e$, axial depth of cut $a_p$ and feed engagement $f_z$ have significant influences on surface roughnesses. The significance order of the effects on milling forces from large to small is $a_e$, $a_p$ and $f_z$. The significance order of the effects on surface roughness from large to small is $a_e$, $f_z$ and $a_p$. Therefore, in order to acquire a higher surface finish quality in practice, the axial cutting depth is better to be appropriately reduced firstly. But for achieving a higher cutting efficiency, the feed engagement is better to be appropriately increased firstly. The absolute value of the relative errors between the finite element simulated milling forces and the experimental ones are smaller than 6%. It means that the finite element model can be used to predict the milling forces for actual milling of components made of the PEEK material. The analytical method used in this paper is possibly used for the analysis of components with easy-to-deform geometrical features.
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