Milling Simulations for the PEEK Biomaterial

Yang Li¹, Xiang CHENG¹*, Sheng-fu DUAN², Xian-hai YANG¹ and Yuan-yong LIU¹

¹School of Mechanical Engineering, Shandong University of Technology, Zibo, 255000, China
²Logistics Supply Department, Zibo Central Hospital, Zibo, 255000, China

*Corresponding author

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Abstract. Polyetheretherketone (PEEK) material has attracted extensive attentions and research in the medical field due to its properties similar to biological bones. But there is a lack of cutting forces in PEEK machining. In this paper, the milling simulations and experiments are carried out taking the milling forces as the study index. The results show that the absolute value of the relative error between the simulation results and the experimental ones are less than 5.6%, which testifies the effectiveness of the finite element model. Through the analysis of variance of the orthogonal experimental data, it can be concluded that both the axial depth of cut \(a_p\) and the radial depth of cut \(a_e\) have more significant influences on milling forces than the feed engagement \(f_z\). The significance order from large to small is the radial depth of cut \(a_p\), the axial depth of cut \(a_e\), and the feed engagement \(f_z\). This study can provide a practical reference for the milling process optimization of the PEEK material.

Introduction

PEEK material is a semi-crystalline polymer which consists of polyaromatic ketones that contributed to stiffness and flexibility of its structure. It has the property of resistance to chemical and radiation, excellent stability in high temperature, good strength and biocompatible as well as higher melting points and glass transition temperatures [1,2]. Due to its enhanced chemical and mechanical structure, PEEK material has been widely used in many applications such as aerospace, semiconductor and electronics [3]. PEEK also have been increasingly employed as biomaterials for trauma, orthopedic, and spinal implants [4].

R. Abdullah, et al. optimized the machining parameters (cutting speed, feed rate and depth of cut) for effectively machining PEEK implant material using carbide cutting tools [5]. Based on the analysis results of Response Surface Methodology (RSM), the optimal machining parameters for the minimum surface roughness values were obtained. R. 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 [6]. RSM approach was applied to design and analyze the optimal combination of tool geometry feature for machining PEEK material.

In the literatures, it can be observed that most of the studies in PEEK material machining mainly focus on the finished surface roughness affected by machining processes, machining parameters and cutting tool geometries. There is limited studies for cutting forces. Because the elastic modulus of PEEK material is relatively smaller than metal materials, cutting forces will cause serious workpiece deformations. Therefore, this paper takes the milling force as the experimental index and carries out finite element simulations and experimental studies on PEEK material.

Finite Element Simulation

Finite Element Modeling

Based on the finite element software Deform-3D, the milling model has been created for the simulation. The three-dimensional model of the tool and workpiece has been created by the
software Solidworks. The milling cutter has the tooth number of 4 and the diameter D of 5mm. The size of workpiece is 3mm×3mm×3mm. The geometric model of the cutter has been simplified to improve the simulation speed. The precutting preparation is conducted to the workpiece model. The created model is shown in Fig. 1.

![Figure 1. Workpiece and tool engagement model.](image)

The reasonable meshing can ensure the simulation quality and reduce the simulation time. The meshing is shown in Fig.2. The tetrahedral mesh type is applied. The local grids are refined with the size of 1 μm for cutting edges and the cutting zone on the workpiece. It can guarantee the simulation precision, shorten the remeshing time and improve simulation speed.

**Single Factor Simulation**

The purpose of single factor simulation is to obtain the influence trend of three key factors (radial cutting depth \(a_e\), axial cutting depth \(a_p\) and feed engagement \(f_z\)) on milling force, and to identify the optimal parameters to design the orthogonal simulation.

**Simulation Parameters.** Table 1 shows the milling parameters for single factor simulation.

| No. | Spindle speed \(n\) (r/min) | Radial depth of cut \(a_e\) (mm) | Axial depth of cut \(a_p\) (mm) | Feed engagement \(f_z\) (mm/z) |
|-----|----------------------------|---------------------------------|-------------------------------|-------------------------------|
| 1   | 12000                      | 0.4, 0.8, 1.2, 1.6, 2.0         | 0.4                           | 0.05                          |
| 2   | 12000                      | 0.4                              | 0.5, 1.0, 1.5, 2.0, 2.5        | 0.05                          |
| 3   | 12000                      | 0.4                              | 0.4                           | 0.03, 0.06, 0.09, 0.12, 0.15   |

When the milling force is computed, the milling force data in directions X, Y, and Z in the stable conditions have been chosen and the noise points have been removed. Then, each average force value is obtained. The resultant force \(F\) of milling is computed by Eq. 1.

\[
F = (F_x^2 + F_y^2 + F_z^2)^{1/2}
\]

Where, \(F_x\) is the milling force in direction X, \(F_y\) is the milling force in direction Y, and \(F_z\) is the milling force in direction Z.

**Results and Discussion.** According to the same analytical processing method, the resultant force values of different milling parameters are computed. The milling forces of different parameters are shown in Fig. 2.

In Fig. 2(a), in these three milling force components, the minimum component is \(F_z\) while the maximum component is \(F_y\). As radial depth of cut \(a_e\) increases, the milling force also increases, the magnitude of its increase is slightly smaller as \(a_e\) increases from 0.4 to 0.8mm, and is larger as \(a_e\) increases from 0.8 to 2.0mm. In Fig. 2(b), in these three milling force components, the minimum component is \(F_z\) while the maximum component is \(F_x\). As axial depth of cut \(a_p\) increases, the milling force also increases, the magnitude of its increase is slightly smaller as \(a_p\) increases from 0.5 to 1.0mm, and is larger as \(a_p\) increases from 1.0 to 2.5mm. In Fig. 2(c), in these three milling force components, the minimum component is \(F_z\) while the maximum component is \(F_x\). As feed...
engagement $f_z$ increases, the milling force also increases, the magnitude of its increase is slightly smaller as $f_z$ increases from 0.03 to 0.06mm/z, and is larger as $f_z$ increases from 0.06 to 0.15mm/z.

![Figure 2](image)

Figure 2. Milling force under different milling parameters, (a) $a_r=0.4$mm and $f_z=0.05$mm/z, (b) $a_r=0.4$mm and $f_z=0.05$mm/z, (c) $a_r=0.4$mm and $a_p=0.4$mm.

**Orthogonal Simulation**

Based on the results of single factor simulation, the factors and levels shown in table 2 are selected for orthogonal simulation.
Table 2. Parameter selection and the resultant force for orthogonal simulation.

| No. | Radial depth of cut \(a_e\) (mm) | Axial depth of cut \(a_p\) (mm) | Feed engagement \(f_z\) (mm/z) | \(F_N\) N |
|-----|-------------------------------|-------------------------------|-------------------------------|----------|
| 1   | 0.7                           | 0.6                           | 0.05                          | 1.93     |
| 2   | 0.7                           | 0.8                           | 0.06                          | 2.75     |
| 3   | 0.7                           | 1.0                           | 0.07                          | 3.62     |
| 4   | 0.7                           | 1.2                           | 0.08                          | 4.58     |
| 5   | 0.8                           | 0.6                           | 0.06                          | 2.16     |
| 6   | 0.8                           | 0.8                           | 0.05                          | 2.98     |
| 7   | 0.8                           | 1.0                           | 0.08                          | 3.89     |
| 8   | 0.8                           | 1.2                           | 0.07                          | 5.08     |
| 9   | 0.9                           | 0.6                           | 0.07                          | 2.42     |
| 10  | 0.9                           | 0.8                           | 0.08                          | 3.11     |
| 11  | 0.9                           | 1.0                           | 0.05                          | 4.02     |
| 12  | 0.9                           | 1.2                           | 0.06                          | 5.13     |
| 13  | 1.0                           | 0.6                           | 0.08                          | 2.85     |
| 14  | 1.0                           | 0.8                           | 0.07                          | 3.68     |
| 15  | 1.0                           | 1.0                           | 0.06                          | 4.47     |
| 16  | 1.0                           | 1.2                           | 0.05                          | 5.37     |

In order to verify the accuracy of simulation results, experiments will be carried out next.

Experiment Results and Contrast

Table 3. Milling forces and relative errors between the simulated values and the experimental ones.

| No. | Simulated (N) | Experimental (N) | Relative error (%) |
|-----|---------------|------------------|--------------------|
| 1   | 1.9           | 2.0              | -5.0               |
| 2   | 2.8           | 2.7              | -3.7               |
| 3   | 3.6           | 3.8              | -5.3               |
| 4   | 4.6           | 4.4              | -4.5               |
| 5   | 2.2           | 2.1              | -4.8               |
| 6   | 3.0           | 2.9              | -4.0               |
| 7   | 3.9           | 3.8              | -3.1               |
| 8   | 5.1           | 5.3              | -4.8               |
| 9   | 2.4           | 2.5              | -3.3               |
| 10  | 3.1           | 3.2              | -3.8               |
| 11  | 4.0           | 4.2              | -4.0               |
| 12  | 5.1           | 5.4              | -4.8               |
| 13  | 2.9           | 3.0              | -5.2               |
| 14  | 3.7           | 3.9              | -4.7               |
| 15  | 4.5           | 4.3              | -5.3               |
| 16  | 5.4           | 5.7              | -6.4               |

From table 3, the absolute value of the relative errors between the simulated values and the experimental ones are smaller than 5.6%. Considering the machine tool vibration, noise in the measurement process and possible errors caused by data processing, the simulation result can be considered as reliable.

Results and Discussion

Table 4. The analysis of variance results.

| Source | Sum of Squares | DF | Mean Square | F-Value | P-Value |
|--------|----------------|----|-------------|--------|---------|
| A      | 1.5764         | 3  | 0.52545     | 90.59  | 0.000   | significant |
| B      | 16.1563        | 3  | 5.38543     | 928.52 | 0.000   | significant |
| C      | 0.0337         | 3  | 0.01122     | 1.93   | 0.225   | not significant |
| Error  | 0.0348         | 6  | 0.00580     |        |         |           |
| Total  | 17.8011        | 15 |             |        |         |             |

Based on the experiments runs, the observed milling force values are between 2.0 and 5.7N. Table 4 shows the analysis of variance (ANOVA) of the orthogonal experiment on the influence of radial depth of cut \(a_e\), axial depth of cut \(a_p\), and feed engagement \(f_z\) for a confidence level of 95%. Based
on 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 influence on milling forces. In this study, based on the P-value and F-value the significant factor in the order from large to small are B (radial depth of cut $a_p$), A (axial depth of cut $a_e$), and C (feed engagement $f_z$). It can be observed that, $a_p$ exerts the strongest influence on the milling force, while $a_e$ has a secondary influence on the milling force, $f_z$ has the smallest influence on the milling force. Therefore, in order to improve the processing efficiency, we can properly increase the feed engagement in the actual PEEK machining.

Summary

For PEEK material milling, the milling force is used as the index to carry out the milling simulation and experimental research. The results show that the absolute value of the relative error between the simulated force results and the experimental ones is less than 5.6%, which means the finite element simulation model for PEEK milling is reliable. Through the analysis of variance of orthogonal experimental data, it can be concluded that the axial depth of cut $a_e$ and radial depth of cut $a_p$ have significant influences on milling forces, while feed engagement $f_z$ has not significant influences on milling forces. The significance order from large to small is radial depth of cut $a_p$, axial depth of cut $a_e$, and feed engagement $f_z$. Therefore, considering the larger deformations in PEEK material during cutting, $a_e$ and $a_p$ should be carefully analyzed and selected in precision PEEK components fabrications.

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