Modeling and Simulations for Polyetheretherketone Milling Forces

Yang Li[1], Xiang Cheng[1,*], Shengfu Duan[2], Xianhai Yang[1] and Yuanyong Liu[1]
[1]School of Mechanical Engineering, Shandong University of Technology, Zibo, 255000, China
[2]Logistics Supply Department, Zibo Central Hospital, Zibo, 255000, China
[*]Corresponding author

***Abstract*—Due to its enhanced chemical and mechanical structure, Polyetheretherketone (PEEK) material has been widely employed as biomaterials for trauma, orthopedic, and spinal implants. But there is a lack of cutting forces in PEEK machining. In this paper, the milling simulations of single factor and orthogonal are carried out taking the milling forces as the study index. According to the results of single factor simulation, it is found that with the increasing of milling parameters a_e, a_p and f_z, the milling force presents a trend of increasing, and the change is very obvious. However, with the increase of spindle speed, the milling force first increases, then decreases, and finally increases. The overall trend is small. Because the spindle speed has little influence on the milling force, so only select a_e, a_p, f_z to conduct the orthogonal simulation. Through the analysis of variance of the orthogonal simulation 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 theoretical reference for the milling process optimization of the PEEK material.**

Keywords—polyetheretherketone; milling force; finite element method; analysis of variance

I. 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].

To determine the effect of cage/spacer stiffness on the stresses in the bone graft and cage subsidence, S. Vadapalli, et al. investigate the effect of cage stiffness on the biomechanics of the fused segment in the lumbar region using finite element analysis [4]. H. Voss, et al. have a study about the wear behaviour of short-glass and carbon-fibre-reinforced composites of polyetheretherketone is investigated under extremely different types of wear loading [5]. Sliding wear tests against smooth steel surfaces were conducted, revealing that the addition of short fibres reduced the wear rate under certain conditions of sliding speed and contact pressure, especially with carbon fibre reinforcement. 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. J. P. 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) [7]. The objective was to evaluate the influence of the reinforcement on the chip thickness ratio, chip deformation, friction angle, shear angle, normal stress and shear stress under prefixed cutting parameters (cutting velocity and feed rate).

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 studies on PEEK material.

II. FINITE ELEMENT SIMULATION

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 of4 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 reasonable meshing can ensure the simulation quality and reduce the simulation time. The meshing is shown in Figure I. 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 [8].

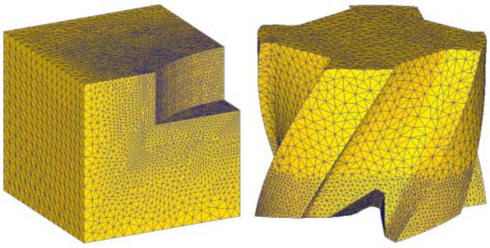

FIGURE I. MODEL MESHING

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

Table I shows the milling parameters for single factor simulation. Figure II shows the simulation process when radial depth of cut a_e=0.4mm, axial depth of cut a_p=0.4mm, feed engagement f_z=0.05mm/z and spindle speed n=11000r/min.

TABLE I. PARAMETER SELECTION FOR SINGLE FACTOR SIMULATION

No.	Radial depth of cut a_e (mm)	Axial depth of cut a_p (mm)	Feed engagement f_z (mm/z)	Spindle speed n (r/min)
1	0.3, 0.6, 0.9, 1.2, 1.5	0.4	0.05	13000
2	0.4	0.5, 1.0, 1.5, 2.0, 2.5	0.05	13000
3	0.4	0.4	0.04, 0.07, 0.10, 0.13, 0.16	13000
4	0.4	0.4	0.05	11000, 12000, 13000, 14000, 15000

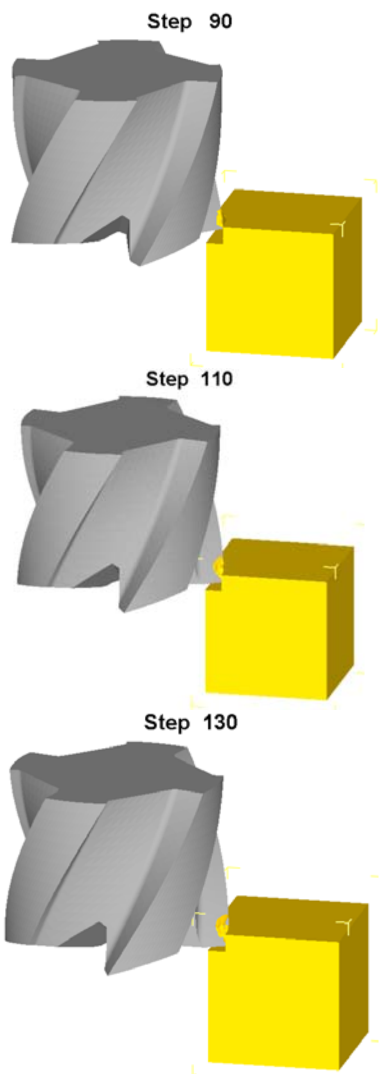

FIGURE II. SIMULATION PROCESS

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).

$$F = (F_x^2+F_y^2+F_z^2)^{1/2} \quad (1)$$

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 indirection Z.

In Figure III(a), 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 0.3 to 0.9mm, and is larger as a_e increases from 0.9 to 1.5mm.In Figure III(b), 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 Figure III(c), as feed engagement f_z increases, the milling force also increases, the magnitude of its increase is slightly smaller as f_z increases from 0.04 to 0.07mm/z, and is larger as f_z increases from 0.07 to 0.16mm/z. In Figure III(d), as spindle speed n increases, the magnitude of force increase is slightly smaller as n increases from 11000 to 13000r/min, the magnitude of force decrease is slightly smaller as n increases from 13000 to 14000r/min, and the magnitude of force increase is slightly smaller as n increases from 14000 to 15000r/min.

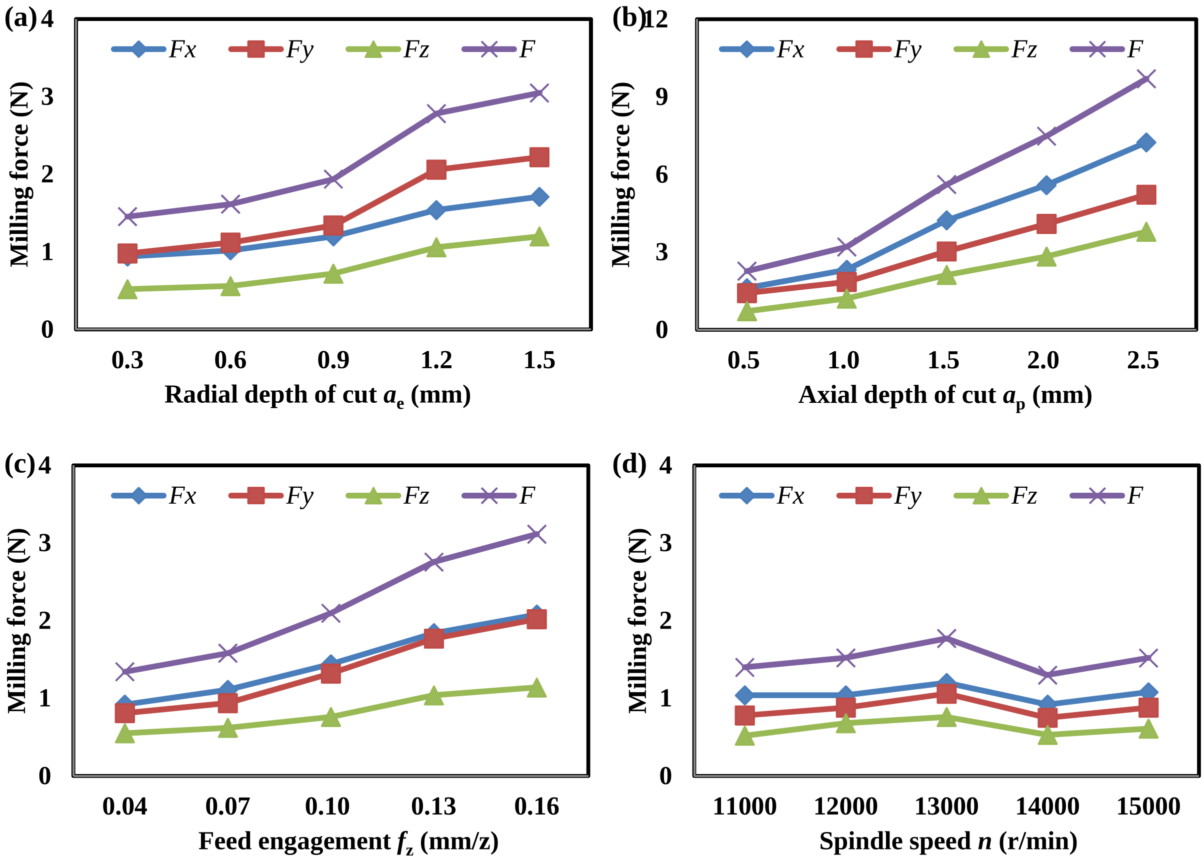

FIGURE III. MILLING FORCE UNDER DIFFERENT MILLING PARAMETERS, (A) A_P=0.4MM, F_Z=0.05MM/Z AND N=13000R/MIN, (B) A_E=0.4 MM, F_Z=0.05MM/Z AND N=13000R/MIN, (C) A_E=0.4MM, A_P=0.4MM AND N=13000R/MIN, (D) A_E=0.4MM, A_P=0.4MM AND F_Z=0.05MM/Z

According to the results of single factor simulation, it is found that the spindle speed has little influence on the milling force, so the spindle speed is set as a constant value (n=14000r/min) in the design of the orthogonal simulation, and the factors and levels shown in Table II are selected for orthogonal simulation. The resultant force of orthogonal simulation is also shown in Table II.

TABLE II. PARAMETER SELECTION FOR ORTHOGONAL SIMULATION.

No.	a_e (mm)	a_p (mm)	f_z (mm/z)	F (N)	No.	a_e (mm)	a_p (mm)	f_z (mm/z)	F (N)
1	0.8	0.8	0.06	2.76	9	1.0	0.8	0.08	2.99
2	0.8	1.0	0.07	3.24	10	1.0	1.0	0.09	3.47
3	0.8	1.2	0.08	3.85	11	1.0	1.2	0.06	4.07
4	0.8	1.4	0.09	4.51	12	1.0	1.4	0.07	4.73
5	0.9	0.8	0.07	2.85	13	1.1	0.8	0.09	3.14
6	0.9	1.0	0.06	3.35	14	1.1	1.0	0.08	3.57
7	0.9	1.2	0.09	3.97	15	1.1	1.2	0.07	4.02
8	0.9	1.4	0.08	4.59	16	1.1	1.4	0.06	4.79

III. RESULTS AND DISCUSSION

Based on the simulation runs, the observed milling force values are between 2.76 and 4.79N. Table III shows the analysis of variance (ANOVA) of the orthogonal simulation 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.

TABLE III. THE ANALYSIS OF VARIANCE RESULTS.

Source	Sum of Squares	DF	Mean Square	F-Value	P-Value	
A	0.20068	3	0.06689	34.45	0.000	significant
B	6.60863	3	2.20288	1134.53	0.000	significant
C	0.00803	3	0.00268	1.38	0.337	not significant
Error	0.01165	6	0.00194			
Total	6.82898	15				

IV. CONCLUSION

According to the results of single factor simulation, it is found that with the increasing of milling parameters (a_e, a_p, f_z), the milling force presents a trend of increasing, and the change is very obvious. However, with the increase of spindle speed, the milling force first increases, then decreases, and finally increases. The overall trend is small. Through the analysis of variance of orthogonal experimental data, it can be concluded that the axial depth of cut a_p and radial depth of cut a_e 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 a_e, a_p, and f_z. Consequently, f_z can be set as large as possible to increase the milling efficiencies and a_e, a_p should be reasonably selected according to the accuracy requirements in PEEK components fabrications.

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