Cutting Force Coefficient for 5 Axis Rough Machining Process on PEEK Material

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***Abstract*—This study aims to provide the value of the cutting force coefficient on the rough 5 axis milling machining process using flat end 4 flute tools on the peek material. The cutting force coefficient is an experimental machining parameter obtained from modeling. The machining process with several spindle rotational speeds produces a morphology chip, which is then used as modeling information to form a cutting force coefficient graph from an experimental stage. Using 5 variations of spindle speed and constant depth of cut, the results obtained for the thickness of the chip resulted in differences in the coefficient of cutting force. At the highest spindle speed, the chip thickness resulting from the machining process is reduced compared to the lowest spindle rotation. Consequently, the value of the cutting force coefficient will increase compared to other lower spindle speeds.**

***Keywords*—5-axis machining, rough machining, cutting force, cutting speed, PEEK**

I. Introduction

The rough machining process is one stage of the manufacturing process that has a large proportion in making a finished product. In this process, the speed of forming the workpiece close to the finished shape impacts reducing production costs. However, increasing the speed of the machining process without sufficient knowledge can actually damage the workpiece and the machine used [1].

Increasing the effectiveness of the rough machining can be done by optimizing the machining area on the workpiece model [1]-[3]. In general, the machining area is only limited to the area that can be reached by the tool based on CAD modeling and the post-processor used by an engineer, so that machine operators can easily improvise the machining area. Another way to increase the effectiveness of the rough machining process is through optimization of machining parameters. Optimization in this section for machining parameters by using the appropriate tool, scheduling the type of tool to the workpiece surface or increasing the cutting speed of the tool can be done by the operator [4]. This requires its own expertise so that the impact of optimization does not harm the production process. In fact, until now, the improvement of the effectiveness of the rough machining is still being carried out to get an advanced system. In an effort to speed up the production process, the machine operators often only increase the value of the feed rate and spindle rotation so that the production process can be carried out quickly. Changes in spindle speed and feed rate in the rough machining process can change the cutting force, while a cutting force that is too large is very likely to damage the workpiece and the machine itself [5], [6].

The defect of the workpiece due to inaccurate cutting forces can occur on 3 axis and 5 axis milling machines. As researched by Tang et al. [7], if there is an error in the tool's positioning on the workpiece's surface, the cutting force will suddenly increase. If this happens to an extreme, then the defect of the tool and workpiece will be difficult to avoid. Thus, the size of the cutting force on the milling machine to the consequential defect of this cutting force can be simulated [8]. However, fluctuations in cutting forces that occur in the machining process are very difficult to control. In other words, force fluctuations always occur due to differences in machining parameters [9].

Cutting force in the machining process is an integral part of the production process of goods. The value of the cutting force is used as a machining process optimization material. In determining the cutting force, chip formation-based modeling aims to determine the coefficient of the cutting force. In this phase, the parameters of shear angle, friction angle and shear yield stress from orthogonal cutting are seen[10]-[12]. Cutting force data from the actual machining process is used as input data for increasing the coefficient. To maintain a constant cutting force peak in 5-axis milling, adjust the feed rate for each tool path [13]. From the research of He et al. [14], it is stated that the cutting point of the tool against the workpiece can be analyzed based on the tool touch area so that the tool path can be formed according to the value of the cutting force to be more effective [15].

The calculation of the cutting force is not limited to metal materials commonly used as raw materials for machining processes. In the last few decades, composite materials have been developed that are widely used in the automotive and aircraft industries [10], [11], [16].

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Empirically, the most popular cutting force mechanistic is the cross model, where each cutting force is influenced by the tool parameters used and the chip morphology of the machining results. Therefore, the coefficient of the cutting force and coefficient of friction must be determined carefully. In general, the cutting force can be determined in two ways: the orthogonal to oblique modeling method and the experimental cutting test. In the orthogonal modeling method, the machining parameters of either the tool or the workpiece are simulated from the magnitude of the segmented edge and shearing force loaded on the rake face [8]. The analytical cutting force on the composite obtained the influence of fiber direction; this can distinguish the analytical cutting force in general.

In addition to modeling and experimental tests, theoretical and experimental combinations are also used for cutting force analysis. The cutting force coefficient is obtained from the machining test based on the machining parameter. To get actual data from cutting conditions, dynamometer and amplifier are needed to collect cutting force data, including radial force, axillary force and tangential force. However, this is very rare in workshops and manufacturing industries due to the high cost of tools and the special need of operators for dynamometer tools. This study will display a graph of the cutting force coefficient used as a reference for operators that do not exist yet to help machine operators know the magnitude of the cutting force, especially the 6 coefficient components commonly used in calculations.

A. State of the Art

This research is useful for the operator predicting cutting force on the initial milling machining process special for PEEK material. This is obtained from the relation of chip morphology produced to simulation of cutting force calculation. By finding out the cutting force coefficient characteristics, the tool's lifetime can be optimized.

II. Method

In this study, experimental data from the cutting test in the form of a morphology chip is used to determine the cutting force coefficient and calibrated with a cutting test for the rough 5-axis milling process. The tool used is a flat end with a diameter of 10mm and the material is HSS-Co (high speed tool steel-cobalt), as shown in Table I, while the workpiece material is PEEK composite with specifications, as shown in Table II.

TABLE I. Tolls Spesification

No	Flat end 10mm Nachi HSS-Co	
1	**Flute**	4 teeth
2	Machining Parameter	Up to 270 SFM, 2700 rpm
3	Shank diameter	10 mm

TABLE II. Material Spesification

No	Mechanical Properties	
1	Modulus young's	11 GPa
2	Poisson's ratio	0.4 v
3	Ultimate Tensile Strength	150 Mpa

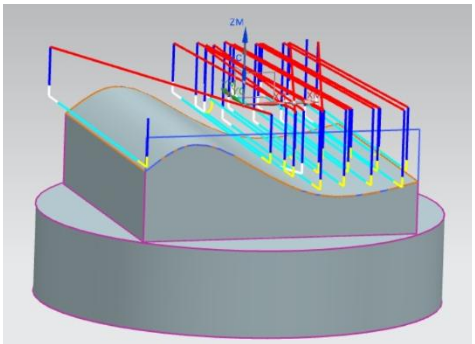

Figure 1. Rough machining tool path.

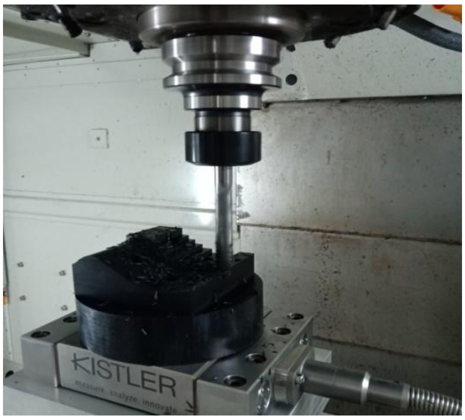

Figure 2. The machining installation.

From the tool and workpiece data above, the machining process is carried out using a 5 axis HURCO 30U milling machine. In this machining process, they are modeling tool path generation using Siemen-NX with ziq method, depth of cut. The machining step over is set constant at 50% of the tool diameter. The tool path has been formed by Siemen-NX with the spindle speed parameter determined by the cutting force data is 3x per process. The cutting chip morphology and cutting force data are averaged to avoid errors due to tool settings. The path generation tool for rough machining process looks like Fig. 1 and machining installation in Fig. 2.

For the machining parameters in the rough machining, as seen on Table III.

TABLE III. The Parameters of Rough Machining Process

No	Parameters	annotation
1	Cutting Speed	(18.84 m/min), (21.98 m/min), (25.12 m/min), (28.26 m/min), (31.4 m/min)
2	Feed Rate	0.05 mm/tooth
3	Depth of cut	5 mm

The data acquisition installation procedure can be seen in Fig. 3 below, where the workpiece in the form of PEEK material is mounted on a table on a 5-axis milling machine.

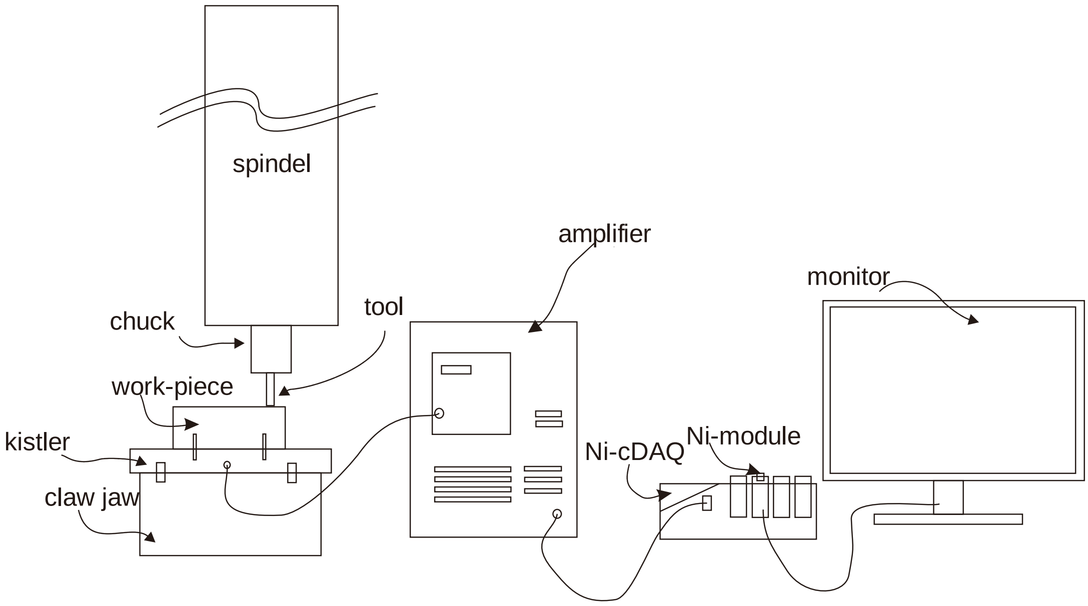

Figure 3. Experimental procedure.

From the picture above, the dynamometer is paired with the table chuck on the machine along with the workpiece. Data from the dynamometer is an analogized signal using an amplifier and collected using data acquisition from National Instrument (NI). The dynamometer used is Kistler type 9192A, and the amplifier is type 5070 from Kistler. Data acquisition is NI 9201 C series module and plugged into an Ethernet chassis NI cDAQ 9188. The chip morphology obtained in each machining process is then analyzed to calculate the cutting force coefficient of the PEEK material.

The magnitude of the cutting force on the *x, y, z* axis is the cutter pitch relationship at each depth of cut, on the flat end tool, which is commonly used for the rough machining process. The formula can be seen in Eq. (1) below.

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta & 0 \\ sin\theta & -cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} F_t \\ F_r \\ F_a \end{bmatrix} \quad \text{..........} \ (1)$$

In one tool path, shifting the cutter location *(cl)* at each cutter contact point (*CC-point*) changes the initial coordinate (*Ow1*) to Coordinal (*Ow + n*) as Eq. (2).

[Xw0,Yw0,Zw0]=Ow0 +n +B(γ(t))(Xw1,Yw1,Zw (2)

Furthermore, the tangential, radial, and axial forces at the cc point can be calculated using Eqs. (3), (4), and (5) below.

$$F_t = K_{tc}bh + K_{te}dz \tag{3}$$

$$F_r = K_{rc}bh + K_{re}dz \tag{4}$$

$$F_a = K_{ac}bh + K_{ae}dz \tag{5}$$

From the above formula, it can be concluded that the force occurs due to the rotation of the tool against the workpiece, both tangential, radial and axial forces is the sum of the instantaneous friction cutting coefficients to chip thickness plus specific shear cutting coefficients to cutting segments. Instantaneous friction cutting coefficients of tangential, radial and axial forces are as follows (6), (7) and (8):

$$F_{cp} = K_{te}dz \tag{6}$$

$$F_{re} = K_{re}dz \tag{7}$$

$$F_{ae}\Delta y = K_{ae}dz \tag{8}$$

Fae in the rough machining process has a very small value, so it is considered 0. So, the instantaneous cutting force coefficient can be calculated using the Eqs. (9), (10), and (11) below.

$$K_{tc} = \frac{\tau}{\sin\phi_n} \frac{\cos(\beta_n - \alpha_n) + \tan i \tan\eta \ sin\beta_n}{\sqrt{cos^2(\phi_n + \beta_n - \alpha_n) + tan^2\eta \ sin^2\beta_n}} \tag{9}$$

$$K_{rc} = \frac{\tau}{\sin\phi_n} \frac{\cos(\beta_n - \alpha_n)\tan i \ - \tan\eta \ sin\beta_n}{\sqrt{cos^2(\phi_n + \beta_n - \alpha_n) + tan^2\eta \ sin^2\beta_n}} \tag{10}$$

$$K_{ac} = \frac{\tau}{\sin\phi_n \cos i} \frac{\sin(\beta_n - \alpha_n)}{\sqrt{cos^2(\phi_n + \beta_n - \alpha_n) + tan^2\eta \ sin^2\beta_n}} \tag{11}$$

The friction angle and shear angle in the machining process can be calculated using Eqs. (12) and (13) below.

$$\tan\beta_n = \tan\beta\cos\eta_c \tag{12}$$

$$\phi_n = tan^{-1}\frac{r_c\cos\alpha_r}{1 - r_c\sin\alpha_r} \tag{13}$$

Chip compression and chip thickness can be calculated by using Eqs. (14) and (15) below:

$$r_c = \frac{h}{h_c} \tag{14}$$

$$h = c \times sin\theta \tag{15}$$

Then tangential edge force coefficient *(Kte)*, can be seen on Eqs. (16) and (17)

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$$F_{cp} = \tau \times b \times r_n \times tan(\frac{\pi}{4} + \frac{\alpha}{2}) \quad (16)$$

$$K_{te} = \tau \times r_n \times tan(\frac{\pi}{4} + \frac{\alpha}{2}) \quad (17)$$

At the same time, the radial edge force coefficient *(Kre)* as seen on Eq. (18)

$$K_{re} = \tau \times r_n \times (1 + \frac{\pi}{2}) \times tan(\frac{\pi}{4} + \frac{\alpha}{2}) \quad (18)$$

Meanwhile, to obtain chip morphology, for each chip formed from the machining process, the length, width and thickness dimensions for each difference in spindle speed are measured. Each chip's parameter, area and thickness were measured more than 5 pcs with a magnification of 40 times to avoid sizing errors in the data collected. The Monocular XSP-13AE microscope used to obtain chip morphology is shown in Fig. 4.

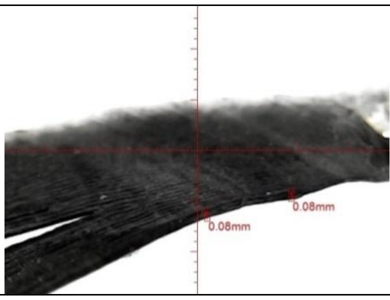
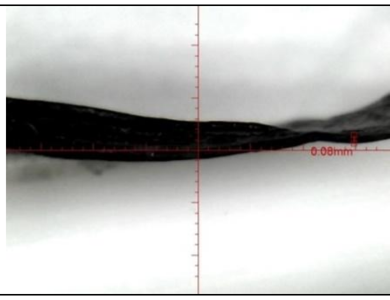
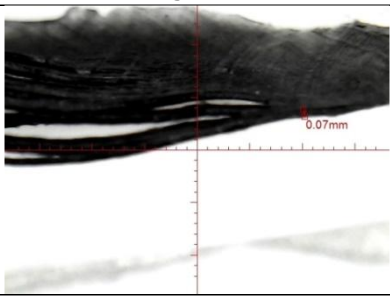
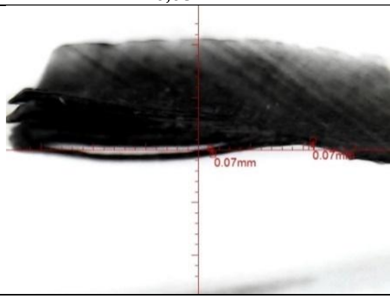
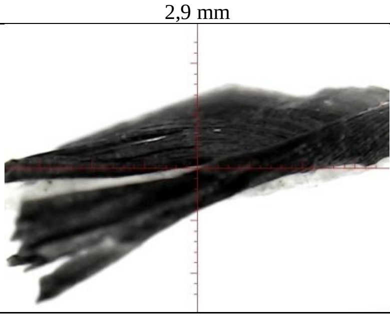
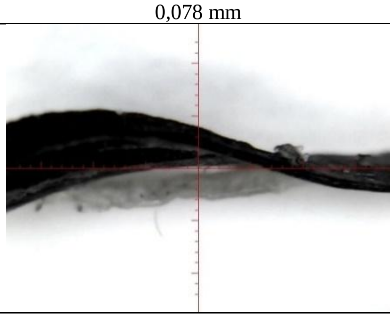
III. Results and Discussion

The research results in determining the instantaneous cutting coefficient, chip morphology from the machining process can be seen in Table IV below.

From the data above, the results for each spindle speed difference produced a morphology chip thickness and chip width used as an analysis to calculate the cutting force from the cutting force signal. Each speed variation of chip surface area and chip thickness changes according to the machining parameters. At the lowest spindle speed of 600 rpm, a cutting speed of 18.84 m/min results in a chip width of 3 mm and a chip thickness of 0.082 mm. At the increase in spindle speed of 800 rpm, 1000 rpm, 1200 rpm and 1400 rpm, the chip width did not change significantly, but the chip thickness decreased, as shown in Fig. 4. At a spindle speed of 800 rpm, the chip thickness is 0.078 mm and gets thinner at a spindle speed of 1200 rpm. The decreasing trend of spindle speed can be seen in Fig. 5 regarding the chip thickness in the rough machining process.

Figure 4. The Monocular XSP-13AE microscope.

TABLE IV. Chip Morphology

No	Spindle Speed	Chip width and length	Chip thickness
1	600 rpm		
		3 mm	0,082 mm
2	800 rpm		
		2,9 mm	0,078 mm
3	1000 rpm		
		2,72 mm	0,074 mm

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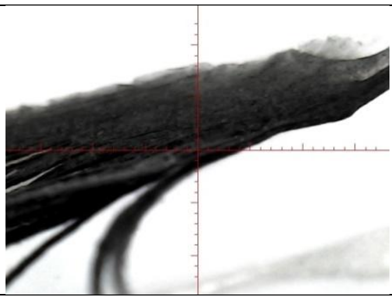
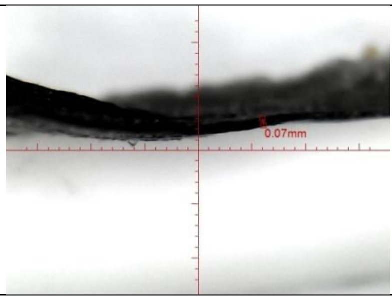
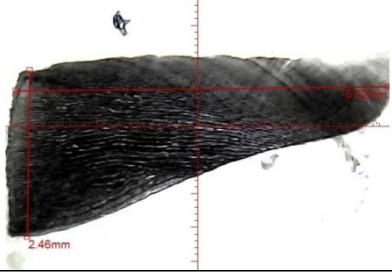
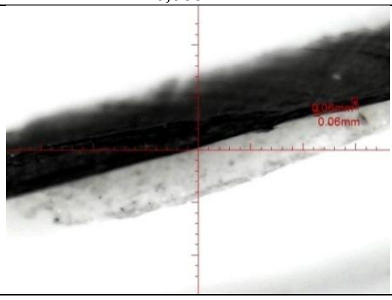
4	1200 rpm		
		2,57 mm	0,066 mm
5	1400 rpm		
		2,46 mm	0,058 mm

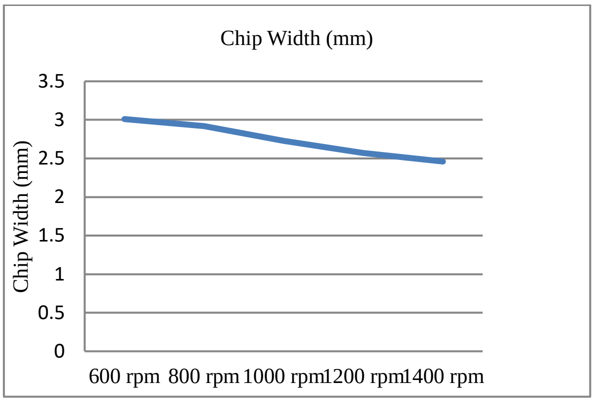


Figure 4. Trend of chip width against spindle speed

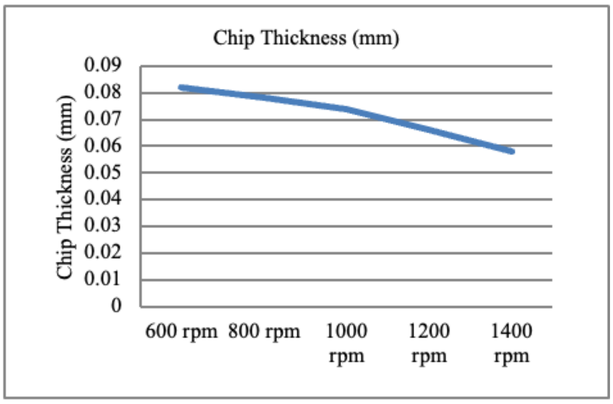


Figure 5. Trend of chip thickness against spindle speed

After the chip width and chip thickness can be known at each spindle speed, the instantaneous cutting force coefficients for tangential, radial and axial forces for PEEK materials in the initial machining process are shown in Fig. 6, 7 and Fig. 8. In Fig. 5, tangential instantaneous cutting force coefficient shows the highest value at a spindle speed of 1400 rpm and a cutting speed of 31.4 m/min.

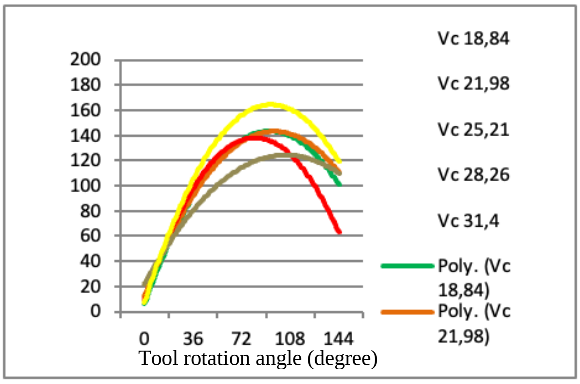


Figure 6. Tangential instantaneous cutting force coefficient (Ktc)

For radial and axial forces, the largest instantaneous value is also found at the highest spindle speed. This can be seen in Fig. 6 and Fig. 7.

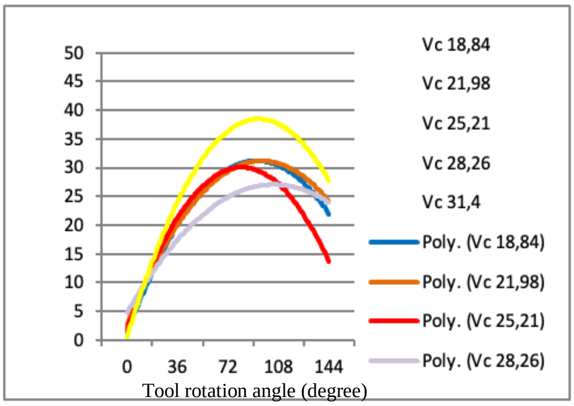


Figure 7. Radial instantaneous cutting force coefficient (Krc)

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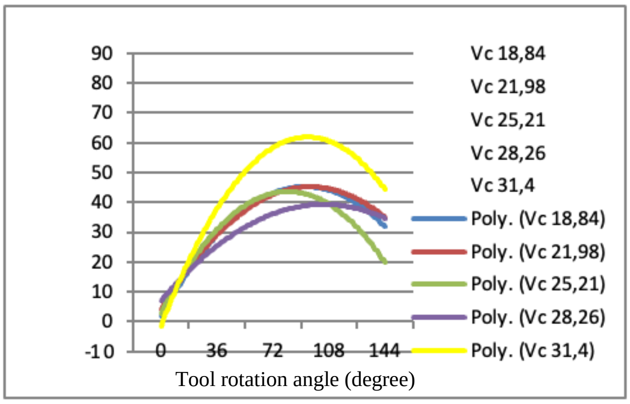

Figure 8. Axial instantaneous cutting force coefficient (Kac)

The trend of increasing spindle speed in the initial machining process in tangential, radial and axial forces is not always followed by a large increase in instantaneous cutting coefficient. The 1400 rpm spindle speed has the highest instantaneous force value of the three components compared to other spindle speeds. Next, instantaneous shear force has a good, fixed value at the lowest spindle speed to the highest spindle speed. Instantaneous tangential edge force coefficient is fixed at 0.011647, while radial edge force coefficient is 0.029933.

IV. Conclusion

The increase in spindle speed from 600 rpm to 1400 rpm in the initial machining process was not followed by an instantaneous increase in the cutting coefficient in the rough machining of PEEK materials simultaneously. However, from the results of the research above, an increase in spindle speed from 600 rpm to 1400 rpm shows significant difference at a speed of 1400 instantaneous cutting coefficients for both radial and axial tangential. This means that even though the chips produced in the machining process are getting thinner, the cutting force produced increases. When the operator changes the spindle speed used to increase the production speed, it can actually endanger material damage to tool damage. This is because the larger the cutting force coefficient, the greater the cutting force value simultaneously has a large value. Based on chip morphology data and cutting force calculation formula as in Eq. (1), greater spindle spin is a smaller chip dimension. In fact, its cutting force coefficient is higher. The total cutting force depends on both components neither *(Fx)* component, *(Fy)* component either *(Fz)* component.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

This work was carried out under the general supervision of H.H. Sutrisno who did all the research. Triyono is responsible for the 5-axis milling machines and cutting tools used. All authors have contributed equally to the writing of the paper and agreed to the final version.

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