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EFFECTS OF CUTTER GEOMETRICAL FEATURES ON MACHINING POLYETHERETHERKETONES (PEEK) ENGINEERING PLASTIC

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ABSTRACT

When polyetheretherketone is used in structural applications it generally undergoes additional machining operations in order to form components. Machining PEEK can be a challenging task for manufacturers, however, especially when using a conventional cutting tool. This paper deals with the influence of a cutter's geometrical features when machining polyetheretherketones engineering plastic on their machining performances. Three categories of end mills were designed and fabricated with varying rake angles, clearance angles and helix angles to investigate effects on machining surface roughness and burr formation. From the investigations conducted, it is evident that end mill geometrical features (rake angle, clearance angle and helix angle) have significant effects on machining surface roughness and burr formation. Increasing the rake angle and helix angle value will improved the machining surface roughness, however, in the case of varying clearance angles, there are no significant results for the surface roughness produced. It could be observed, however, that a 12° clearance angle produced better surface roughness compared to other angles. The findings from the deliberately conducted experiments can be used for the development of high performance cutting tools, especially for machining polyetheretherketones engineering plastic material.

Keywords**:** Machining; polyetheretherketones; end mill angles; surface roughness.

INTRODUCTION

Polyetheretherketones (PEEK) are one of the thermoplastic polymers that has excellent stability in high temperatures, resistance to chemicals and radiation, good strength and is biocompatible (Denault & Dumouchel, 1998). It is a semi-crystalline polymer which consists of polyaromatic ketones that contribute to toughness, stiffness and the flexibility of its structure. Due to its good chemical and mechanical structure, PEEK thermoplastic has been widely used in the aerospace, electronics and medical industries. PEEK was commercialized in implant components for orthopedic and trauma applications because of its biodegradable characteristics and non-allergic reactions compared to metal implants (Kurtz & Devine, 2007). Figure 1 shows an example of PEEK application for a medical implant. Processing some plastics can be easily scaled up to meet the increasing demand for product parts. Incorporating plastic technologies (for example, injection molding) means that the economics of production are viable on a larger scale, while complex shapes can be formed as required to aid device fabrication. However, it is often not economically viable to manufacture an injection molding tool for prototype designs or short production runs. Under such circumstances, it is common to employ a machining process on PEEK polymer materials to form the components. Traditional manufacturing methods associated with metallic implants are generally not satisfactory for polymeric materials. Polymers are relatively soft when compared to implant alloys and this can create manufacturing problems related to machining, deburring, and cleaning operations.

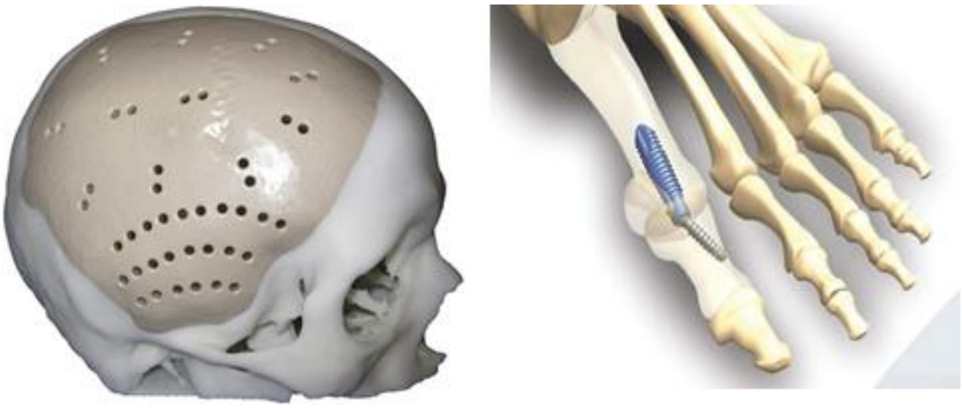


Figure 1. PEEK application for medical implant (Xilloc, 2013)

Very few research works dealing with machining PEEK have been reported. In most cases, research only concentrated on the effect of cutting parameters on machining performances. In addition, machining was done using a lathe machine, in which the cutting tool geometry is not complex compared to end milling. Davim and Mata (2006) investigated the effect of PCD (Polycrystalline Diamond) tool inserts when turning PEEK material with different cutting speeds (150 m/min, 250 m/min and 377 m/min) and feed rates (0.05 mm/rev, 0.1 mm/rev and 0.2 mm/rev). They found that increasing the cutting speed contributed to high cutting pressure and minimized the surface roughness value, and increasing the feed rate, led to low cutting pressure and increased the surface roughness value.

Mata, Gaitonde, Karnik, and Davim (2009) also investigated the interaction effects of cutting speed and feed rate towards the machinability of reinforced and unreinforced PEEK with PCD cutter insert. They found that a high feed rate will increase the machining power and decrease the cutting pressure at specific cutting speeds. The research also showed that reinforced PEEK has poor machinability compared to unreinforced PEEK. Although the reinforced elements can improve strength and stiffness properties, the machining cost is high, as reinforced PEEK is extremely abrasive. In a later work, Mata et al. (2009) studied the physical cutting model of reinforced PEEK CF30 and unreinforced PEEK chip thickness, chip deformation, shear stress and normal stress after machining. They demonstrated that PEEK CF30 has high normal and friction stress compared to unreinforced PEEK because of the existence of fiber. Meanwhile, chip deformation of PEEK CF30 was smaller compared to unreinforced PEEK because of the fragility of the carbon fiber.

It can be seen in the literature that most of the research in machining PEEK engineering plastic only focuses on few areas such as machining parameters, cutting tool material and fiber reinforced types. Little attention is given to the effect of cutter geometry on machining performance due to its complexity. Chatelain and Zaghbini (2012) observed that cutter geometrical features can influence cutting performances, especially in surface finish, dimensional tolerances and cutting forces. Thus, investigation of the effect of cutter geometrical features is important for effectively machining polyetheretherketones (PEEK) engineering plastic material.

END MILL GEOMETRICAL FEATURES

The geometrical features of end mill consists of a core diameter, inscribed circle diameter, rake angle, clearance angle and helix angle. Each of the geometric features has their specific function and will significantly affect the machining performance. Figures 2 and 3 show the end mill geometrical terminology and the cutting angles respectively. Rake angle can have a significant effect on the cutting forces, stress distribution, chip deformation, cutting edge stiffness and rigidity of the tool (Izamshah, Yuhazri, Hadzley, Ali, & Subramonian, 2013). An end mill with a positive rake angle will improve machinability, thereby producing a lesser cutting force and cutting temperature. Baldoukas, Soukatzidis, & Demosthenous (2008) investigated the decrease in cutting force with increasing rake angle. Meanwhile, (Shirpurkar, Bobde, Patil, & Kale, 2012) found that rake angle influenced the cutting forces, power consumption and surface finish. The cutting forces and power were minimized when using a tool with high rake angle, and produced a good surface finish. However, too large a rake angle reduces the edge strength of the tool due to friction and stress distribution. Thus, a proper selection of rake angle value is vital and needs to be considered for specific application.

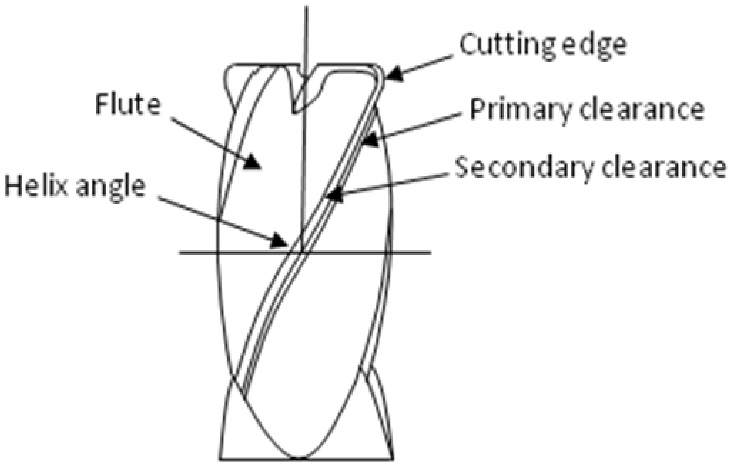


Figure 2. End mill geometrical terminology.

Relief angle can also affect the performance of a cutting tool. Relief angle or clearance angle is the angle between the cut surface and the clearance flank on the cutter. To obtain a good tool life a high value of clearance angle is preferred. However higher values of clearance angle tend to weaken the cutting edge, which becomes over-heated because of poor heat transfer from the cutting edge. In the case of end mills, smaller clearance angles reduce the chip space for the same number of teeth. In such cases, primary and secondary clearances are provided. The value of clearance angles also depends on the diameter of the end mill. Smaller end mills have larger relief angles.

As an example, machining of CFRP composite requires a high relief angle to control the bouncing of the fiber and prevent the tool from rubbing with the workpieces. A high relief angle can also enhance the cutting edge quality of the laminate polymer. Tunc and Budak (2012) experimentally investigated the influence of clearance angle on process damping and stability. They demonstrated that process damping increased regularly with increased clearance angle value.

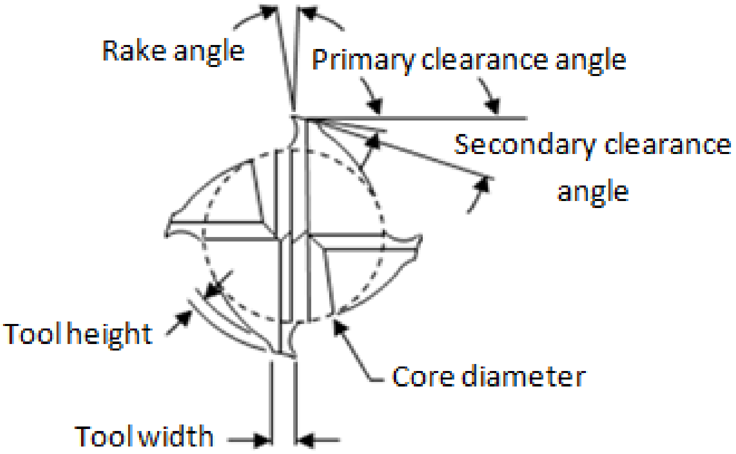


Figure 3. End mill cutting angles.

Helix angle is the angle formed by a line tangent to the helix and a plane through the axis of the cutter or the cutting edge angle, which a helical cutting edge makes with a plane containing the axis of a cylindrical cutter. A large helix angle can reduce tool deflection by transferring stress vertically which allows the end mill to produce vertical chip ejection. Yang, Chang, Lee, Kim, & Ko (2003) investigated the shear forces and friction of different end mill helix angles of 30º, 40º and 50º. They demonstrated that shear stress and friction energy increased as the helix angle increased. In addition, greater shearing action results in increased speeds and feeds and faster stock removal.

EXPERIMENTAL DESIGN AND SETUP

Using a CNC tool cutter grinder Michael Deckel S20 Turbo machine, design parameters and proper wheel geometries were determined to produce the end mill. A two flutes carbide flat end mill with a diameter of 10mm and total length of 70mm was fabricated to analyze the effect of variable rake angle, helix angle and clearance angle on machining polyetheretherketones (PEEK) engineering plastic material, as depicted in Table 1. Table 2 lists the rake angles, helix angles and clearance angles designed for the experiment. In this experiment, three categories of end mills were designed to investigate the effects on machining surface roughness and burr formation. The first end mill category was designed to maintain varying rake angles of 5^o, 10^o and 15^o with a constant clearance angle of 10^o and helix angle of 30^o (Figure 4 (a)). The second category was designed to maintain varying clearance angles of 6^o, 8^o, 12^o and 14^o with a constant rake angle of 14^o and helix angles of 30^o (Figure 4 (b)). The following category was designed to maintain varying helix angles of 20^o, 25^o, 30^o , 35^o and 45^o with a constant rake angle of 8^o and clearance angles of 6^o as depicted in Figure 5. Other design factors were held constant. Each of the fabricated end mills were then measured using a tool microscope for accuracy.

Table1. End mill specification.

Material	Diameter	Overall length	Flute length	Bottom	No. of flute
Micro grain carbide rod HRC 55	10 mm	70 mm	40 mm	Flat	2

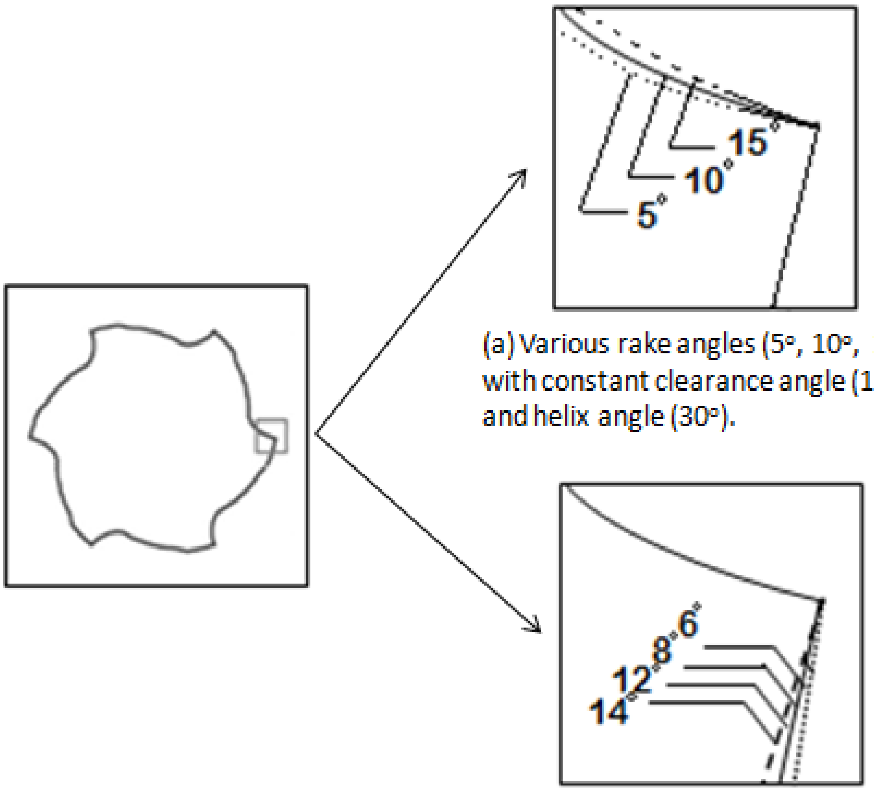
Table 2. Design parameter for end mill.

Tool	Rake angle (Degree)	Clearance angle (Degree)	Helix angle (Degree)
1	5	10	30
2	10	10	30
3	15	10	30
4	14	6	30
5	14	8	30
6	14	12	30
7	14	14	30
8	8	6	20
9	8	6	25
10	8	6	30
11	8	6	35
12	8	6	40

Table 3. Workpiece and machining parameters used in the experiment.

Workpiece	
Polyetheretherketones	TECAPEEK
Tensile strength at yield	95Mpa
Rockwell hardness	M99
Density	1.32g/cm^3
Melting temperature	343ºC
Glass transition temperature	143ºC
Coefficient of thermal expansion	50 x 10E-6 mK
Machining parameter	
Cutting speed	6000rpm
Depth of cut	5mm
Feed	100mm/min
Coolant	Dry cut

The workpiece used in the experiment was a polyetheretherketone (PEEK) thermoplastic polymer sheet manufactured by TECAPEEK. Slot milling cutting tests were conducted using a 5-axis Deckel Maho milling machine to investigate the machining surface roughness with respect to the changes in rake angle, helix angle and clearance angle. After the machining process, the surface roughness value and burr formation were measured using a Mitutoyo SJ-301 portable surface roughness tester and optical microscope respectively. Table 3 shows the workpiece and machining parameters used for the slot milling experiment.



(a) Various rake angles (5°, 10°, 15°) with constant clearance angle (10°) and helix angle (30°).

(b) Various clearance angles (6°, 8°, 12°, 14°) with constant rake angle (14°) and helix angle (30°).

Figure 4. End mill fabrication of various rake angles and clearance angles.

EXPERIMENTAL RESULTS

Table 4 shows the machining surface roughness on PEEK material of varying rake angles, clearance angles and helix angles. The result show that a combination of 15° rake angle, 10^o clearance angle and 30^o helix angle result in a minimum surface roughness of 0.26µm, and a combination of 8° rake angle, 6^o clearance angle and 25^o helix angle result in a maximum surface roughness of 1.21µm. It can be seen that increasing the rake angle value will improve the surface roughness. This is due to the increase in tool sharpness, which helps the chip eject easily. In addition, the sharp tool produces optimum shear stress on soft polymer plastics and allows for faster feed rates to cut the PEEK polymer. There were no significant results for varying clearance angle, on the surface roughness produced, however, it could be observed that a 12° relief angle produced better surface roughness compared to other angles. One of the possible reasons is the ability of the end mill to maintain its stability and thus reduce the friction between the tool and the workpiece surface.

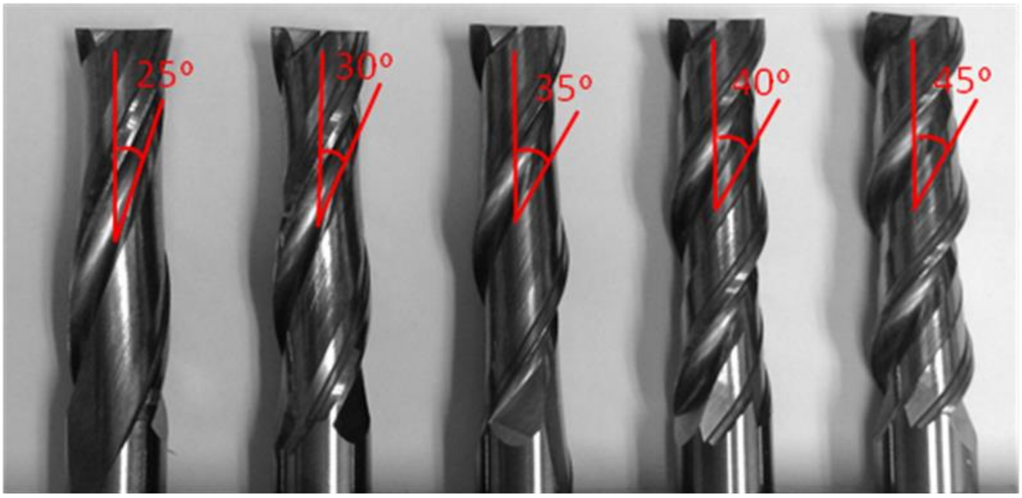


Figure 5. Various helix angles (25°, 30°, 35°, 40°, 45°) with constant clearance angles (6°) and rake angle (8°).

In another case, there was a significant improvement in the surface roughness values by increasing the helix angle, which agreed with results of other studies. A high helix angle can effectively help the chip extraction away from the cutting zone whilst reducing the stuck-chip disruption. Machining surface roughness can thus be improved by increasing the helix angle value. The findings agree with previous studies by Moetakef Imani (2009), and Chatelain and Zaghbini (2012) which demonstrated that a helical cutter with a large helix angle produced a smooth surface and low cutting force distribution compared to a small helix angle.

Table 4. Experimental measured values of surface roughness.

Tool	Rake angle	Clearance angle	Helix angle	Surface roughness (µm)			
				Run 1	Run 2	Run 3	Average
1	5	10	30	0.69	0.66	0.67	0.67
2	10	10	30	0.34	0.35	0.37	0.35
3	15	10	30	0.28	0.26	0.25	0.26
4	14	6	30	0.92	0.89	0.9	0.90
5	14	8	30	0.83	0.84	0.86	0.84
6	14	12	30	0.72	0.7	0.69	0.70
7	14	14	30	0.8	0.78	0.77	0.78
8	8	6	20	1.1	1.11	1.13	1.11
9	8	6	25	1.23	1.2	1.21	1.21
10	8	6	30	0.85	0.85	0.84	0.85
11	8	6	35	0.83	0.81	0.8	0.81
12	8	6	40	0.32	0.34	0.31	0.32

The burr formation characteristic at the machined edge surfaces changes with the varying rake angle values. Large rake angles produced thin and continuous chip morphology at the side machining surface which shows that the high shear stress occurred at the PEEK polymer as shown in Figure 6. The high shear stress increased the strain rate of the PEEK polymer due to the behavior of thermoplastic properties, which exhibited high elastic strain proportional with the stress increment (Fried, 2003; Sheikh-Ahmad, 2009).

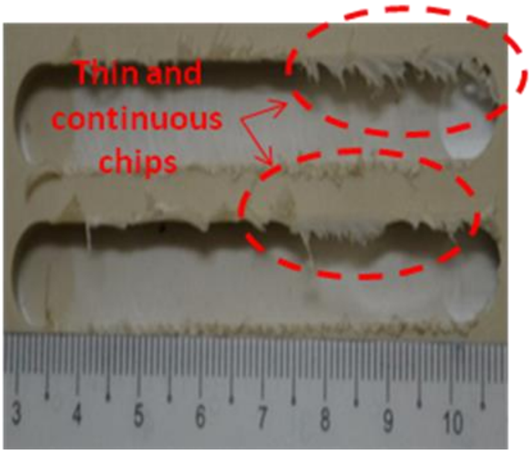


Figure 6. Chip morphology and burr formation with large rake angle.

For varying the clearance angles, there was no significant change in the characteristic. All burr formation had the same characteristic which was a long and continuous chip, as shown in Figure 7. Although there is no significant effect of varying clearance angles on burr formation, the proper selection of clearance angle in terms of stability and machining vibration is necessary (Tunç & Budak, 2012).

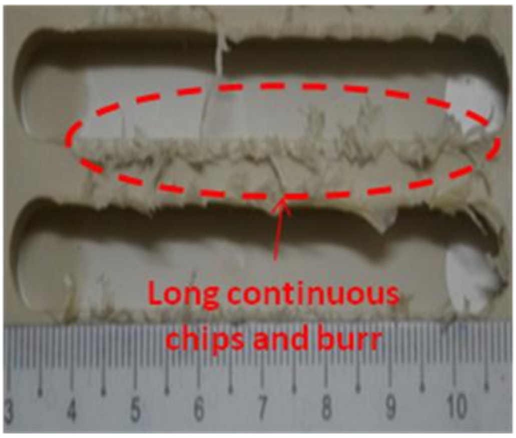


Figure 7. Long and continuous chip morphology and burr formation with varying clearance angles.

The burr formation characteristic at the machined edge surfaces changes with the varying helix angle values. It is found that a large helix angle will result in thick and continuous chips compared to a low helix angle, as a result of high shearing force. Figure 8 shows chip formation for a large helix angle cutting tool which indicates the polymeric softening as a result of localized heat on cutting zone (Sheikh-Ahmad, 2009; Yang et al., 2003).

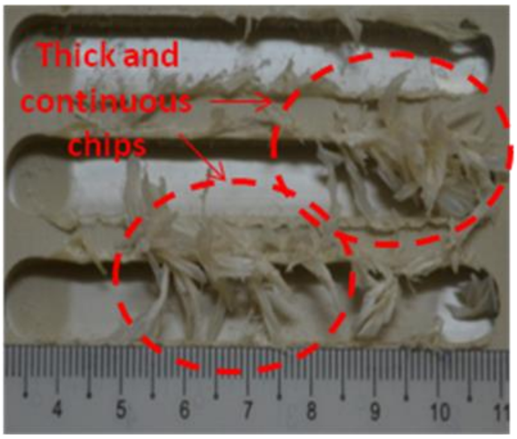


Figure 8. Thick and continuous chip morphology and burr formation with large helix angle.

CONCLUSIONS

From the investigations conducted, it is evident that end mill geometrical features (rake angle, clearance angle and helix angle) have significant effects on machining surface roughness and burr formation. Increasing the rake angle and helix angle value will improve the machining surface roughness, however, in the case of varying clearance angle, there are no significant results for the surface roughness produced. It could be observed, however, that a 12° relief angle produced better surface roughness compared to other angles. The findings from the deliberately conducted experiments can be used for the development of high performance cutting tools, especially for machining polyetheretherketones (PEEK) engineering plastic material.

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