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Machinability Evaluation in Unreinforced and Reinforced PEEK Composites using Response Surface Models

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ABSTRACT: Polyetheretherketone (PEEK) composite belongs to a group of high performance thermoplastic polymers and is widely used in structural components. In order to improve mechanical and tribological properties, short fibers are added to unreinforced thermoplastics. Both unreinforced and reinforced PEEK composites find potential applications in manufacturing processes due to high specific properties and hence it is necessary to investigate the machining performance. This paper presents the application of response surface methodology (RSM)-based approach to study the machinability aspects of unreinforced PEEK, reinforced PEEK with 30% of carbon fibers (PEEK CF30) and 30% of glass fibers (PEEK GF30) composites with cemented carbide (K10) tool machining. The experiments are planned as per full

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factorial design of experiments and second order mathematical models are developed to establish the relationships between cutting conditions (cutting speed and feed rate) and machinability aspects (cutting power and specific cutting force). Analysis of variance is performed to check the adequacy of the models. The parametric analysis indicates that cutting power increases with increase in feed rate while the specific cutting force decreases for both unreinforced and reinforced composites. The results show that K10 tool provides better machinability for PEEK and PEEK CF30 materials as compared to PEEK GF30 work material.

KEY WORDS: polyetheretherketone (PEEK), cemented carbide (K10) tool, turning, cutting power, specific cutting force, response surface methodology (RSM).

INTRODUCTION

THE COMPOSITE MATERIALS are widely used in aerospace and automotive industries, medical applications, biomechanics, robots, and machines due to their excellent property profile [1,2]. The thermoplastic composites have been introduced to provide good toughness, better environmental resistance, and high temperature performance, which replace thermoset materials that are presently facing with the problems of brittleness and sensitivity to water [3].

Polyetheretherketone (PEEK) composite belongs to a group of high performance thermoplastic polymer that exhibits excellent properties due to its semi-crystalline character and molecular rigidity of its repeating units [4]. The PEEK composites are commonly used in triboapplications due to the combination of thermo-mechanical properties and relatively low friction and wear [5,6]. The addition of short fibers to unreinforced thermoplastics further increases stiffness, strength, hardness, and service temperature [7,8] and reduces wear, coefficient of friction, and thermal expansion coefficient [9]. The reinforced carbon fiber provides maximum rigidity and load bearing capacity [10,11], whereas the reinforced glass fiber provides high temperature service [4]. As a result of these properties and potential applications, there is a need to understand the machining of unreinforced and reinforced PEEK composites.

Even though, PEEK composites are produced as near net shapes, the machining has to be performed in the final manufacturing stage to get the finished components. The successful performance of machining operation is affected by work material properties and is expressed in terms of 'machinability.' Cutting force, cutting power, specific cutting force, tool wear, tool life, and surface roughness are some of the criteria, which are used to evaluate the machinability. Although, the machinability refers to work materials, the performance of machining depends upon several factors

such as cutting conditions, tool material, tool geometry, and machining operations [12].

The investigative study on machinability by Rahman et al. [13] on carbon/PEEK composites showed that some form of polymer softening action is responsible for achieving a better surface finish rather than tool geometry. Chambers and Bishop [14] compared the machinability analysis of carbon/epoxy and carbon/PEEK composites machining with different cutting tools. Davim et al. [7] studied the effects of cutting speed and feed rate on machining force, specific cutting pressure, and surface roughness in turning of PEEK and PEEK GF30 materials using polycrystalline diamond (PCD) tool. Davim and Reis [8] carried out an experimental research on PEEK GF30 machining with PCD and cemented carbide (K20) tools. The machinability aspects such as power, specific cutting pressure, and surface roughness were compared. Davim and Mata [15] presented a study on experimental physical model of orthogonal cutting on PEEK and PEEK CF30 materials. The influence of reinforcement on chip thickness ratio, chip deformation, friction angle, shear angle, normal stress, and shear stress under prefixed cutting conditions was evaluated and then the physical model was compared with Merchant equation.

The present work is aimed at determining the effects of cutting conditions (cutting speed and feed rate) on machinability (cutting power and specific cutting force) during turning of unreinforced PEEK, reinforced PEEK with 30% of carbon fibers (PEEK CF30), and 30% of glass fibers (PEEK GF30) composites with cemented carbide (K10) cutting tools. The interaction effects of cutting speed (v) and feed rate (f) on cutting power (P) and specific cutting force (K_s) have been analyzed using second order mathematical models developed through response surface methodology (RSM). The RSM not only reduces the cost and time, but also provides required information about the interaction effects with minimum number of experiments [16].

EXPERIMENTAL DETAILS

Experimental Design

In order to develop the mathematical models based on experimental data, careful planning of experimentation is essential. Hence, it is essential to have a well-designed set of experiments that can substantially reduce the number of experiments as compared to classical experimental design. In the present study, two parameters, namely, cutting speed and feed rate are considered and the ranges of the parameters were selected based on preliminary investigations. Three levels for cutting speed (50, 100, and 200 m/min) and four levels for feed rate (0.05, 0.10, 0.15, and 0.20 mm/rev) are selected.

Table 1 presents an experimental layout plan based on full factorial design (FFD) of experiments [16], which consists of 12 experiments.

Experimentation

PEEK, PEEK CF30, and PEEK GF30 work materials supplied by ERTA® were used throughout the investigation. Table 2 summarizes the mechanical and thermal properties of work materials tested. The extruded workpieces of 100 mm length and 50 mm diameter were turned using cemented carbide (K10)

Table 1. Experimental layout plan, computed values of cutting power and specific cutting force as per FFD.

	Actual process parameter settings		Cutting power (W)			Specific cutting force (MPa)		
Trial no.	*v* (m/min)	*f* (mm/rev)	PEEK	PEEK CF30	PEEK GF30	PEEK	PEEK CF30	PEEK GF30
1	50	0.05	32.85	31.96	38.84	395.8	385	468
2	50	0.10	48.06	56.61	75.55	289.5	341.05	455.1
3	50	0.15	70.21	86.15	92.01	281.97	345.97	369.53
4	50	0.20	86.88	117.59	109.89	261.68	354.18	331
5	100	0.05	90.93	76.18	94.44	547.8	458.9	568.9
6	100	0.10	107.53	118.42	119.54	323.9	356.7	360.05
7	100	0.15	145.08	194.85	173.9	291.33	391.27	349.2
8	100	0.20	172.09	206.97	170.07	259.18	311.7	256.13
9	200	0.05	116.75	131	152.15	350.6	393.4	456.9
10	200	0.10	203.9	187.25	241.33	306.15	281.15	362.35
11	200	0.15	283.78	301.1	345.25	284.07	301.4	345.6
12	200	0.20	330.9	411.09	448.15	248.43	308.63	336.45

Table 2. Properties of PEEK, PEEK CF 30, and PEEK GF 30 composites.

Mechanical and thermal properties	PEEK	PEEK CF30	PEEK GF30
Tensile modulus (MPa)	4400	7700	6300
Rockwell hardness	M105	M102	M99
Charpy impact resistance (KJ/m^2)	Without fract.	35	35
Tensile strength (MPa)	110	130	90
Melting temperature (°C)	340	340	340
Density (g/cm^3)	1.31	1.41	1.51
Coefficient of thermal expansion at <150°C [m(m K)]	$50 \times 10e{-}6$	$25 \times 10e{-}6$	$30 \times 10e{-}6$
Coefficient of thermal expansion at >150°C [m(m K)]	$110 \times 10e{-}6$	$55 \times 10e{-}6$	$65 \times 10e{-}6$

cutting tool (DCMW 11T304H13A). A 'SDJCL 2020 K11' type tool holder was used and the tool geometry was: Rake angle: 7°; Clearance angle: 0°; Cutting edge angle: 93° and Cutting edge inclination angle: 0°.

The experiments were conducted as per FFD (Table 1) on a 'Kingsbury MHP 50' CNC lathe. The lathe is equipped with 18 kW spindle power and maximum rotational speed of 4500 rpm. The experiments were randomized in order to avoid systematic errors. Two millimeter depth of cut was kept constant throughout the investigation.

In order to acquire the cutting force (F_c), a 'Kistler®' piezoelectric dynamometer 9121 with a load amplifier was employed. The data acquisitions were made through a piezoelectric dynamometer using interface RS-232 to update the amplifier and PC using appropriate 'Dynoware Kistler®' software. The machinability is evaluated in terms of cutting power (P) and specific cutting force (K_s), which are calculated from the following equations:

$$P = F_c v \tag{1}$$

$$K_s = \frac{F_c}{f * d} \tag{2}$$

where, d is the depth of cut. The computed values of P and K_s for PEEK, PEEK CF30, and PEEK GF30 composites are listed in Table 1.

DEVELOPMENT OF RSM-BASED MATHEMATICAL MODELS

RSM is a tool, which is designed to develop the mathematical relationship to link the controllable parameters to the experimental responses so as to explore the effect of parameters on responses. In the present work, second order RSM-based mathematical models of cutting power (P) and specific cutting force (K_s) have been developed for each of the work materials in terms of two process parameters, namely, cutting speed (v) and feed rate (f). The nonlinear response surface equations of P and K_s are given by [16]:

$$P = a_0 + a_1 v + a_2 f + a_{12} vf + a_{11} v^2 + a_{22} f^2 \tag{3}$$

$$K_s = b_0 + b_1 v + b_2 f + b_{12} vf + b_{11} v^2 + b_{22} f^2 \tag{4}$$

where, $a_0, \ldots b_{22}$: regression coefficients of mathematical model to be determined.

The values of regression coefficients of linear, quadratic, and interaction terms of the mathematical models are determined by the following formula [16]:

$$B = (X^{\mathrm{T}}X)^{-1}X^{\mathrm{T}}Y \tag{5}$$

where,

B : matrix of parameter estimates
X : calculation matrix includes linear, quadratic and interaction terms
X^{T}: transpose of X
Y : matrix of response.

RESULTS AND DISCUSSION

Mathematical Models for Cutting Power and Specific Cutting Force

The mathematical models as determined by regression analysis to predict the cutting power and specific cutting force during turning of PEEK, PEEK CF30 and PEEK GF30 materials using K10 carbide tool are given below:

CUTTING POWER

$$P_{(\mathrm{PEEK})} = -23.835 + 0.800743v + 161.8467f + 7.410457vf - 0.002259v^2 - 938.667f^2 \tag{6}$$

$$P_{(\mathrm{PEEKCF30})} = -15.7383 + 0.828879v - 165.877f + 9.017371vf - 0.002903v^2 + 1013.667f^2 \tag{7}$$

$$P_{(\mathrm{PEEKGF30})} = 48.03958 - 0.49855v + 32.21667f + 10.7426vf + 0.002427v^2 - 1134.67f^2 \tag{8}$$

SPECIFIC CUTTING FORCE

$$K_{\mathrm{s}(\mathrm{PEEK})} = 500.4058 + 2.195343v - 3777.7f + 2.557257vf - 0.010325v^2 + 9552.333f^2 \tag{9}$$

$$K_{\mathrm{s}(\mathrm{PEEKCF30})} = 423.0154 + 1.656214v - 1966.97f - 1.18031vf - 0.006979v^2 + 6475.667f^2 \tag{10}$$

$$K_{\mathrm{s}(\mathrm{PEEKGF30})} = 709.0592 - 1.18424v - 3027.12f + 2.985543vf + 0.002429v^2 + 5851.667f^2 \tag{11}$$

where, v is in m/min; f in mm/rev; P in W and K_{s} in MPa.

Table 3. ANOVA for cutting power and specific cutting force mathematical models.

	Sum of squares		Degrees of freedom		Mean square		
Response	**Regression**	**Residual**	**Regression**	**Residual**	**Regression**	**Residual**	***F*-ratio**
Material: PEEK							
Cutting power	93,206	671	5	6	18,641	112	166.67**
Specific cutting force	60,221	15,272	5	6	12,044	2545	4.73**
Material: PEEK CF30							
Cutting power	129,441	1610	5	6	25,888	268	96.50**
Specific cutting force	19,142	7897	5	6	3828	1316	2.91*
Material: PEEK GF30							
Cutting power	155,555	1984	5	6	31,111	331	94.07**
Specific cutting force	61,310	15,443	5	6	12,262	2574	4.76**

*Significant at 75% confidence interval.
**Significant at 95% confidence interval.

Testing Adequacy of Mathematical Models

The analysis of variance (ANOVA) [16] was employed to test the adequacy of the models for a confidence interval. The ANOVA table consists of sum of squares and degrees of freedom. In order to perform ANOVA, sum of squares is usually performed into contributions from regression model and experimental error. As per this method, if the calculated value of *F*-ratio of the regression model is more than the standard tabulated value of table (*F*-table) for a given confidence interval, then the model is considered to be adequate within the confidence interval. Table 3 presents the adequacy of the developed mathematical models.

The coefficient of determination (R^2) is used to test the goodness of fit of the developed models. R^2-value provides a measure of variability in the observed values of response and can be explained by the controlled variables and their interactions. The R^2-values of the developed models are shown in Table 4, which indicate correlation between the variables and the responses and the significance of the developed mathematical models.

Table 4. R^2-values of cutting power and specific cutting force models.

Response	PEEK	PEEK CF30	PEEK GF30
Cutting power	0.993	0.988	0.987
Specific cutting force	0.798	0.708	0.799

Table 5. Prediction error of cutting power and specific cutting force models for the experimental data.

	Percentage prediction error		
Response	PEEK	PEEK CF30	PEEK GF30
Cutting power	6.05	5.32	8.56
Specific cutting force	9.19	6.33	7.27

Determining Models Accuracy

The accuracy of a mathematical model is given by:

$$\Delta = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{y_{i,\text{expt}} - y_{i,\text{pred}}}{y_{i,\text{pred}}}\right| \tag{12}$$

where,

$y_{i,\text{expt}}$: experimental value of response corresponding to ith trial,

$y_{i,\text{pred}}$: RSM model predicted value of response corresponding to ith trial,

n: number of trials.

The prediction error of developed RSM-based mathematical models is within 10% for all the work materials tested as illustrated in Table 5. The comparison of the RSM model predicted values and the experimental values of P and K_s for PEEK, PEEK CF30, and PEEK GF30 composites as per FFD are shown in Figures 1 and 2, respectively.

Analysis of Results based on Mathematical Models

The developed mathematical models are used to predict the responses by substituting the values of cutting speed and feed rate within the ranges selected. The variations of responses with respect to process parameters are plotted for each of the work materials and are shown in Figures 3 and 4.

As seen in Figure 3, the cutting power increases with increase in cutting speed for any given value of feed rate for both unreinforced and reinforced

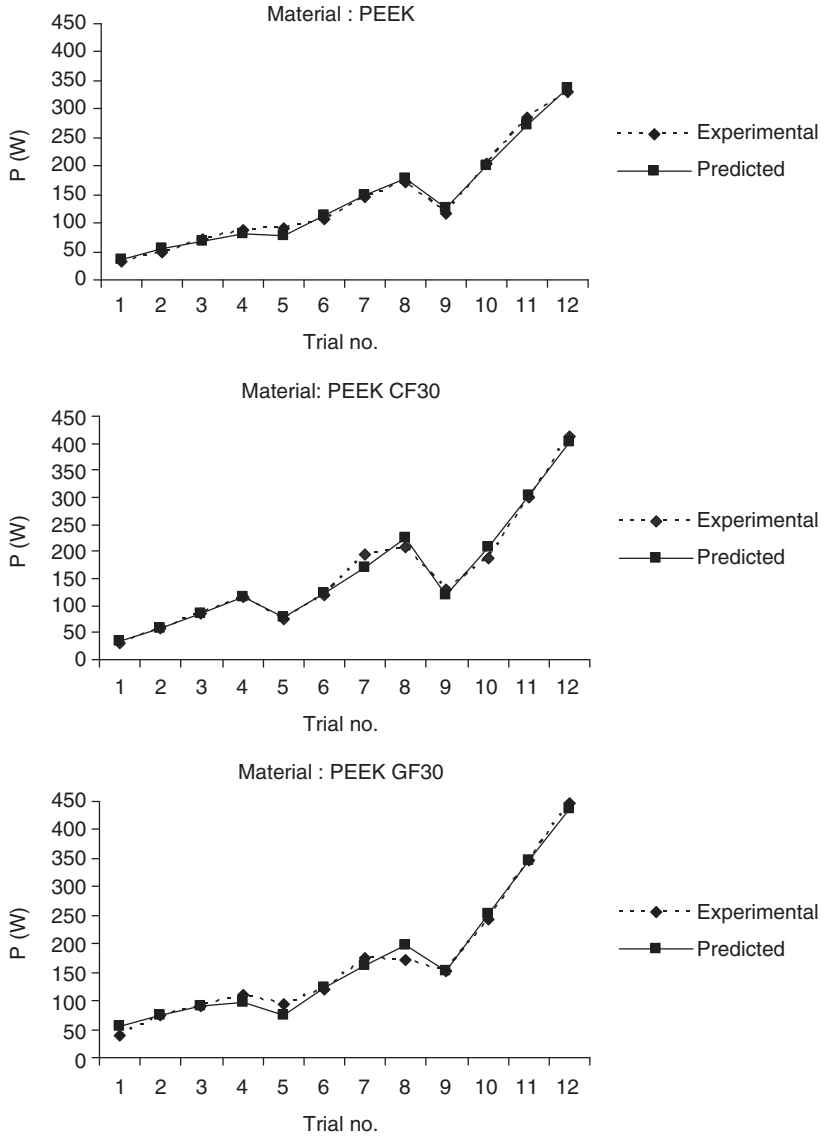

Figure 1. *Experimental and predicted values of cutting power.*

composites tested. For a given cutting speed, cutting power has a tendency to increase with increase in feed rate and hence, the cutting power is sensitive to variations in both cutting speed and feed rate as observed from Figure 3. Further, it is also observed that, minimum cutting power is required at

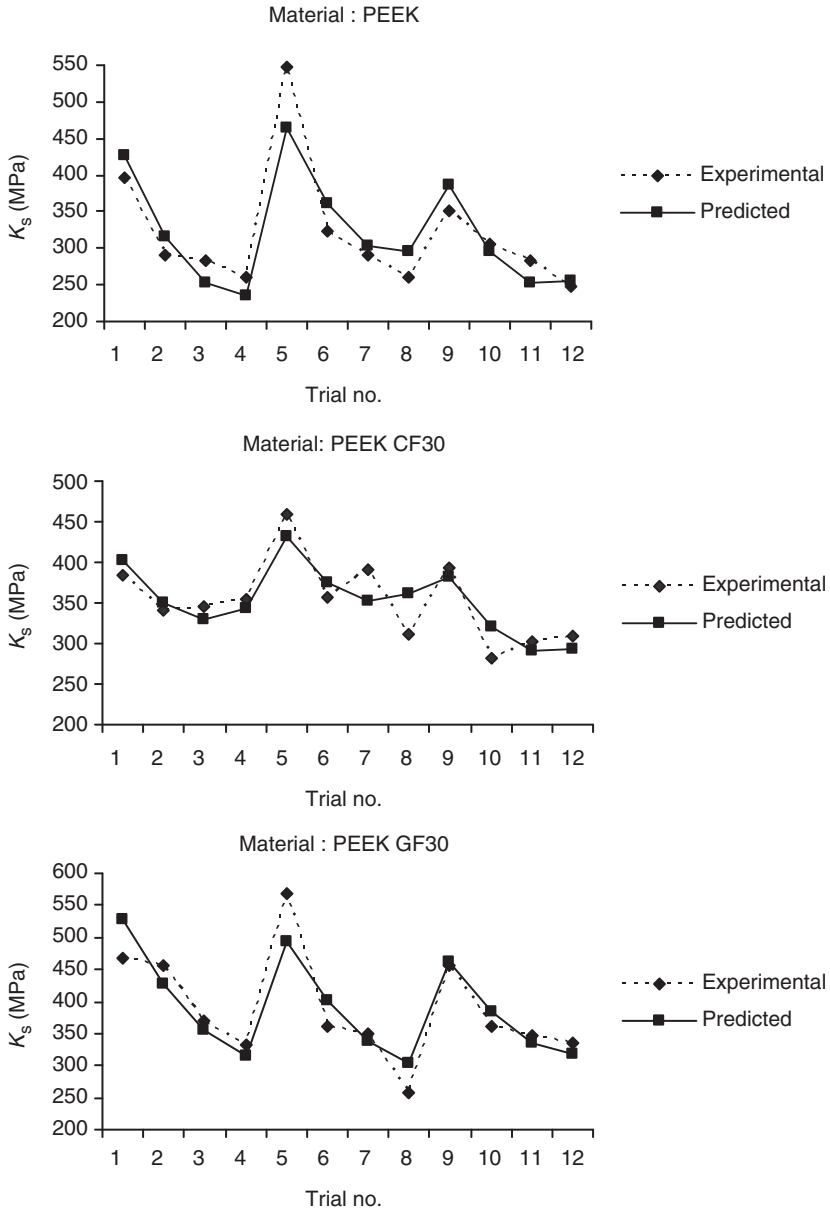

Figure 2. *Experimental and predicted values of specific cutting force.*

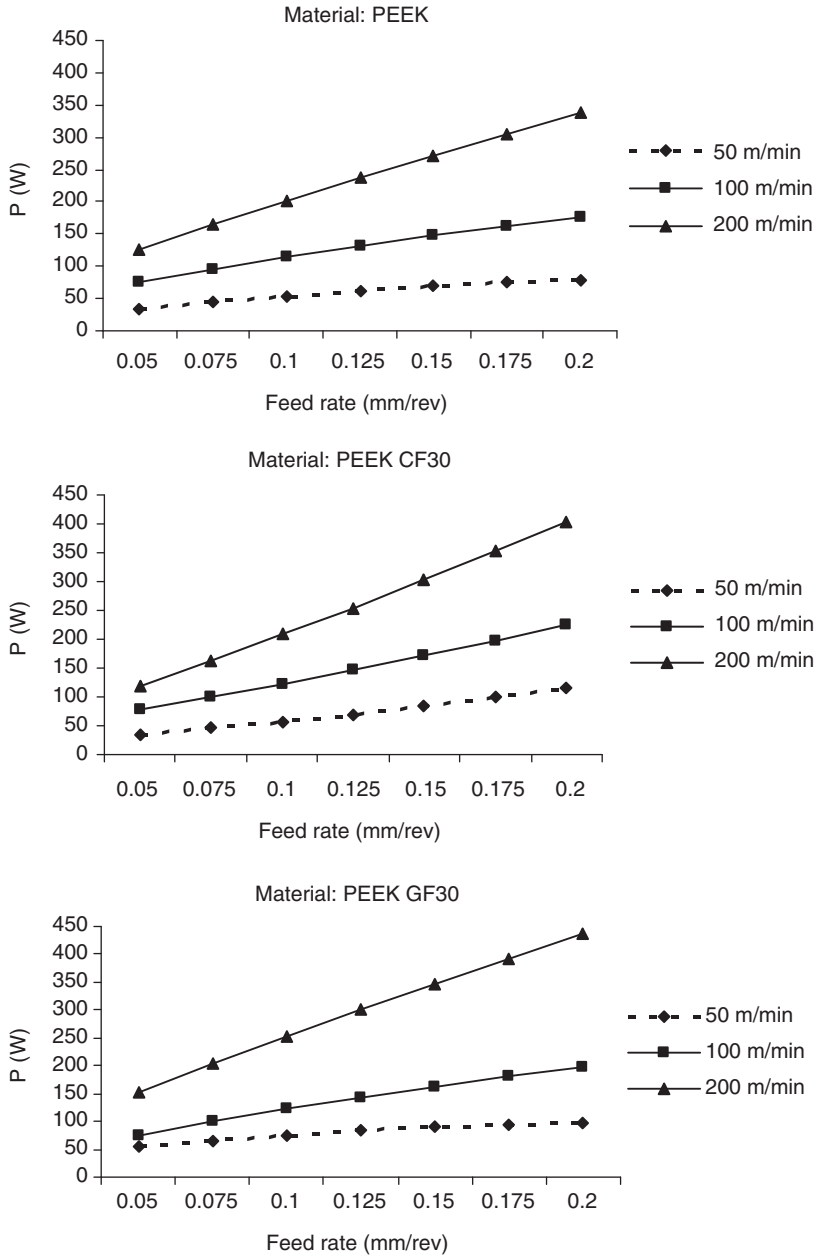

Figure 3. *Effect of cutting speed and feed rate on cutting power.*

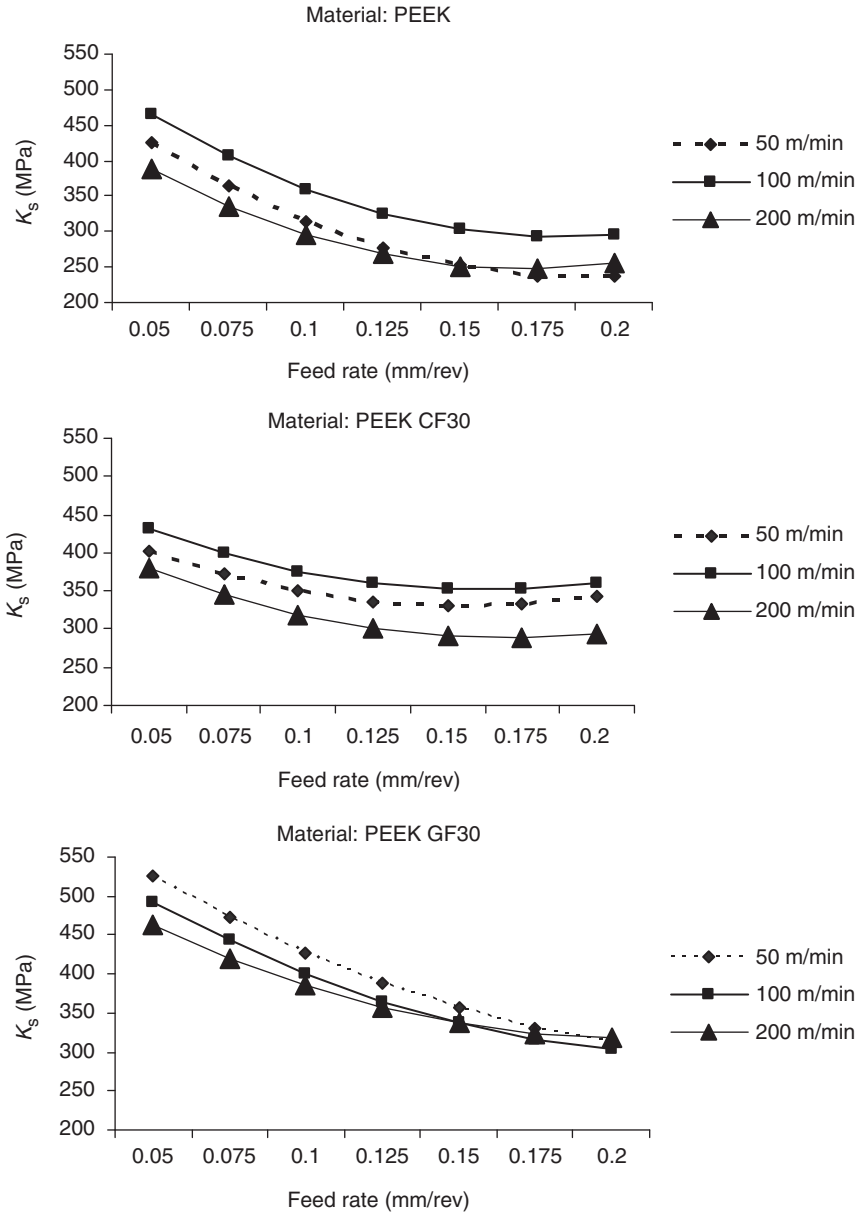

Figure 4. *Effect of cutting speed and feed rate on specific cutting force.*

low values of both cutting speed and feed rate for all the materials tested. Figure 3 also indicates that the cutting power required is more for reinforced composites (PEEK CF30 and PEEK GF30) as compared to unreinforced PEEK composites.

Figure 4 shows the variation of specific cutting force with respect to feed rate for different values of cutting speed. It is found that the specific cutting force sharply decreases with increase in feed rate for both unreinforced and reinforced composites. It is also observed that, for a given feed rate, the specific cutting force is less sensitive to cutting speed variations. The specific cutting force is more in PEEK GF30 material as compared to PEEK and PEEK CF30 materials as observed in Figure 4. Further, it is seen that the higher feed rate generates the smaller cutting force, which is almost independent of cutting speed.

Figures 3 and 4 show that, cutting power and specific cutting force both depend on cutting speed and feed rate for all the work materials tested. Further, it is found that the cutting power is less at lower values of feed rates, while the specific cutting force is more. It is also clear from the above analysis that minimum cutting power requirement may not be suitable for achieving minimum specific cutting force for a given material. Parametric analysis also reveals that even though the addition of reinforcements to unreinforced PEEK improves the material properties, the cutting power and specific cutting force increase, and hence affect the machinability of both carbon and glass fiber-reinforced PEEK composites.

CONCLUSIONS

The response surface methodology (RSM) based approach to study the machinability characteristics of PEEK, PEEK CF30, and PEEK GF30 composites using cemented carbide (K10) tool are presented in this paper. Based on the experimental results and parametric analysis, the following conclusions are drawn.

- The cutting power increases with increase in feed rate while the specific cutting force decreases for a given cutting speed for all the work materials.
- The minimum cutting power results from a combination of lower values of cutting speed and feed rate. On the other hand, higher values of feed rate are required to achieve minimal specific cutting force which is almost independent of cutting speed.
- The machinability of PEEK CF30 and PEEK GF30 composites is poor as compared to PEEK material.

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