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Full Length Research Paper

Derivation of statistical models to predict roughness parameters during machining process of PEEK composites using PCD and K10 tools

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In many scientific fields, non-linear regression based models are of great utility to perform curve adjustment of experimental data. This concept is used in the present study in order to construct adequate adjusted models enabling to make predictions for the different roughness parameters characterizing machining of PEEK composites when using PCD and K10 tools. The adjusted data were obtained by using design of experimental methods and only the main factors affecting roughness during machining of PEEK composites were retained. Since, analysis of variance performed on experimental results has revealed that feed is the main cutting factor that influences surface roughness, nonlinear regression is conducted only in terms of this parameter.

Key words: Non-linear regression, machining process, PEEK composites, PCD tool, K10 tool, roughness parameter.

INTRODUCTION

Organic machined materials that are currently used involve plastic materials reinforced with glass fibers (GFRP´s) or with carbon fibers (CFRP´s). Actually, a large amount of research activity concentrates in the area of machinability of these special materials. Machining is a manufacturing process in which one uses a cutting tool to eliminate material excess until obtaining the desired form and dimensions of a mechanical component. Since the Industrial use of materials made up form polymeric matrix composites requires respecting rigorous dimensional specifications, a suitable development of machining process criteria in this field is needed. PEEK is an acronym abbreviation for Polyether Ether Keton which is a thermoplastic with high thermal and mechanical efficiencies.

The addition of carbon fibers increases resistance and rigidity of PEEK; PEEK CF30 (PEEK reinforced with 30% volumetric glass fiber) and PEEK GF30 (PEEK reinforced with 30% volumetric glass fiber) constitute cost-effective alternatives to stainless steel and other metallic materials in strongly corrosive industrial applications. They are employed in various fields such as car, space, oil or gas industries. The increasing number of applications for which PEEK represents an outstanding implementation has augmented the request about enhancing new manufacturing processes for PEEK parts. Traditional operations in the field of metal manufacturing are thus considered for PEEK. The major problem to deal with is then studying the optimal conditions which allow cutting, drilling, milling, grinding and turning in the best possible manner. In this context, it is important to recall that users of PEEK CF30 and PEEK GF30 are often confronted to huge technical difficulties when projecting to machine these materials. These difficulties result form the fact that knowledge and experience gained in the field of conventional materials

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cannot be transposed as it is to PEEK composites because machinability conditions of these last are completely different from those of conventional materials. PEEK composites contain two phases, with highly different mechanical and thermal properties. This yield complex interaction between matrix and reinforcements which affects machining process of these special materials. The situation is thus far from materials which are constituted from only one phase; metals for example. Moreover, machinability of PEEK composites is strongly affected by fibers reinforcement rate (Davim and Mata, 2008), (Petropoulos et al., 2008), (Davim and Mata, 2007, 2006), (Davim et al., 2003).In this work, a design of experiment is introduced in order to evaluate and to optimize the factors intervening in machining of non reinforced PEEK, PEEK CF30 and PEEK GF30. The objective is to identify the factors which significantly affect the level of roughness parameters of a part as obtained by this particular manufacturing process. This is enables as a first step to retain only the most important factors in order to simplify modeling of roughness during machining operations. Predictive models are finally derived by performing non-linear regression of experimental data where the different roughness parameters are given as function of the main factors such that they are assessed from a statistical approach technique based on design of experiment and analysis of variance.

Proposed regression model for surface roughness

Instead of restricting the problem to the well-known field of linear regression models, which could be estimated very basically, the broader family of non-linear regression models is considered in the present work. Attention will be focused on one-variant models, that is to say models in which there exists only one dependant variable, since they are much simpler to deal with than multivariate models where several dependent variables are involved. One-variant models are by far the most frequently encountered statistical models in practice. Good comprehension which could result from working with them could be of precious help to get further insight when dealing the more complicated multivariate models. All the postulated one-variant models that are considered in the following assume that roughness can be expressed as a single valued function of the most influent parameter during machining, namely the feed rate. Nonlinear statistical models could so be expressed under a large variety of mathematical functions, however the most common used ones are those called quadratic, cubic, inverse, or logarithmic regressions (Spanier and Oldham, 1987).

Explicit relationships that give these various regressions are as follows:

Quadratic: $$R_{i=a,q} = b_0 + b_1 f + b_2 f^2 \quad (1)$$

Cubic: $$R_{i=a,q} = b_0 + b_1 f + b_2 f^2 + b_3 f^3 \quad (2)$$

Inverse: $$R_{i=a,q} = b_0 + \frac{b_1}{f} \quad (3)$$

Logarithmic: $$R_{i=a,q} = b_0 + b_1 \log(f) \quad (4)$$

Power: $$R_{i=a,q} = b_0 + f^{b_1} \quad (5)$$

Composite: $$R_{i=a,q} = b_0 b_1^{\,f} \quad (6)$$

Where b_0, b_1, b_2, b_3 are parameters which depend on the considered regression.

Once a particular regression mode is selected, parameters fixing the mathematical adjusting curve which fit the best experimental data could be easily determined.

Identifying the well-matched non linear regression model

Procedures which deal with optimal curve fitting of experimental data are available as tools that perform adjustment according to a given regression model. A special regression model can thus be derived by using the well known SPSS software package. In order to identify the equation which adapts the best a given statistical data let's recall the main parameter which is used to qualify the method: Sig. This parameter represents the level of significance, that is to say probability for obtaining the result by a pure random chance. If the level of significance is very small, less than 0.05 for example, then the correlation is significant and the null hypothesis can be rejectted. In other words, a low level of significance indicates that the results are high probably not randomly scattered. The other parameter which is used to qualify a regression model is the coefficient of determination (R^2). This statistical parameter measures how successful the fit is in interpolating the actual set of data. R^2 can take any value between 0 and 1. A value of R^2 which is closer to 1 indicates that a major proportion of variance is accounted for by the regression model.

Materials and methods

In the present work, the ranges of machining process parameters were selected based on the previous investigations performed on PEEK materials by (Mata, 2008). The composite materials used in this study are the non reinforced PEEK, PEEK CF30, and PEEK GF30 which were supplied by ERTA ®.

These materials were provided in the form of cylinders having a diameter of 50 mm and a 100 mm length. The operation of machining was realized using the CNC turn, Kingsbury MHP 50, which was equipped with cemented carbide cutting tool K10. This turn is digitally controlled. External roughness Ra (Arithmetic height average, the most common parameter used to characterize machining process and to perform product quality control) and Rq (Root mean square roughness which represents the standard deviation of the height profile distribution) were measured with the profilometer, Hommeltester T1000. The profilometer is made up from a unit which advances and a probe which sweeps the part according to a

Table1. Assignment of levels and codes to the factors

	Level	Code
Cutting speed (m/min)	200	1
	100	2
	50	3
Feed rate (mm/rev)	0.05	1
	0.10	2
	0.15	3
	0.20	4

Table2. The full factorial array used in design of experiment

Test	Cutting speed	Feed rate
1	1	1
2	1	2
3	1	3
4	1	4
5	2	1
6	2	2
7	2	3
8	2	4
9	3	1
10	3	2
11	3	3
12	3	4

fixed direction. All the tests were achieved without lubricating and a total of twelve combinations were performed according to a full factorial design of experiment. The considered factors included the cutting speed and the feed rate. Three levels for the cutting speed and four levels for the feed rate were considered according to Table 1. In all cases, a constant cut depth was maintained at the value of 2 millimeters. The twelve tested configurations are recalled in Table 2 where notations of the intervening parameters and their selected levels are given.

RESULTS AND DISCUSSION

Evaluation of the relative effect of factors on the surface roughness during machining process is carried out through the technique of analysis of variance (ANOVA), (Taguchi, 1990; Yang and Tarng, 1998). The analysis of variance (ANOVA) is a statistical method which makes it possible, for a given experiment, to say if variability of results could be attributed to identifiable sources with their respective number of degrees of freedom. According to the statistical theory of decision, analysis of the effect of significance of a parameter on qualitative characteristics of results could be carried out by means of the F-test (Fisher-test). ANOVA results for roughness parameters and estimation of their relative effect were obtained directed from the Table of reaction as obtained by means of Matlab command anovan. From the obtained ANOVA diagram, one could notice that for the range of parameters considered in this study, which deals with PEEK composites materials machined by using PCD and K10 tools, the feed rate is the parameter having the most influence on roughness. It is followed by the cutting speed.

Figures (1-6) represent the chart of all the non-linear regression models for the two roughness parameters Ra and Rq as function of feed rate.

The various mathematical models as determined by regression for Ra and Rq which are associated to PEEK cut with PCD tool are:

Quadratic:

$$R_a = 0.467 - 4.94\,f + 87.333\,f^2,\quad R_q = 0.733 - 10.133\,f + 128\,f^2$$

Cubic:

$$R_a = 1.937 - 51.7f + 507.3f^2 - 1120f^3,\quad R_q = 2.367 - 62.09f + 594.7f^2 - 1244f^3$$

Inverse:

$$R_a = 2.901 - \frac{0.136}{f},\quad R_q = 3.676 - \frac{0.174}{f}$$

Logarithmic:

$$R_a = 5.206 + 1.69\ln(f),\quad R_q = 6.653 + 2.174\ln(f)$$

Power:

$$R_a = 21.18\,f^{\,1.319},\quad R_q = 27.91\,f^{\,1.347}$$

Compound:

$$R_a = 0,239\,(315030)^{f},\quad R_q = 0,283\,(446904)^{f}$$

The various mathematical models as determined by regression for Ra and Rq which are associated to PEEK CF30 cut with PCD tool:

Quadratic:

$$R_a = 0.706 - 7.13\,f + 88.33f^2,\quad R_q = 0.892 - 8.663f + 105.7f^2$$

Cubic

$$R_a = 0.233 + 7.9f - 46.67f^2 + 360f^3,\quad R_q = 0.537 + 2.66f + 4f^2 + 271.1f^3$$

Inverse:

$$R_a = 2.724 - \frac{0.12}{f},\quad R_q = 3.276 - \frac{0.143}{f}$$

Logarithmic:

$$R_a = 4.758 + 1.493\ln(f),\quad R_q = 5.690 + 1.771\ln(f)$$

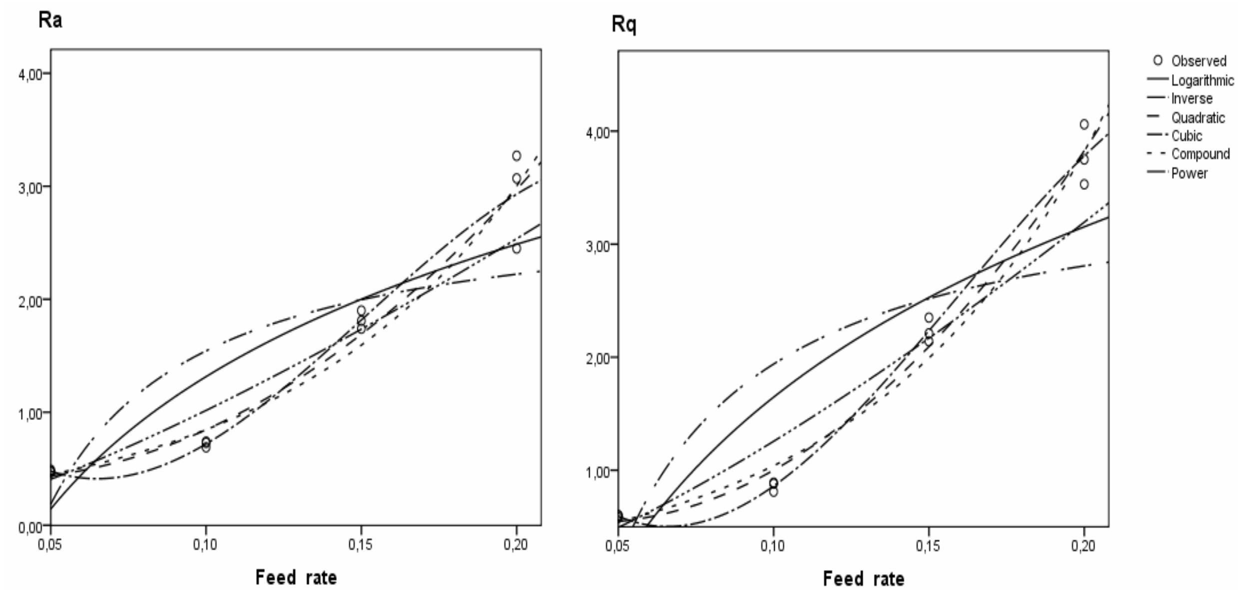

Figure 1. Ra and Rq as function of the feed rate for all non-linear regression models; PEEK using PCD tool

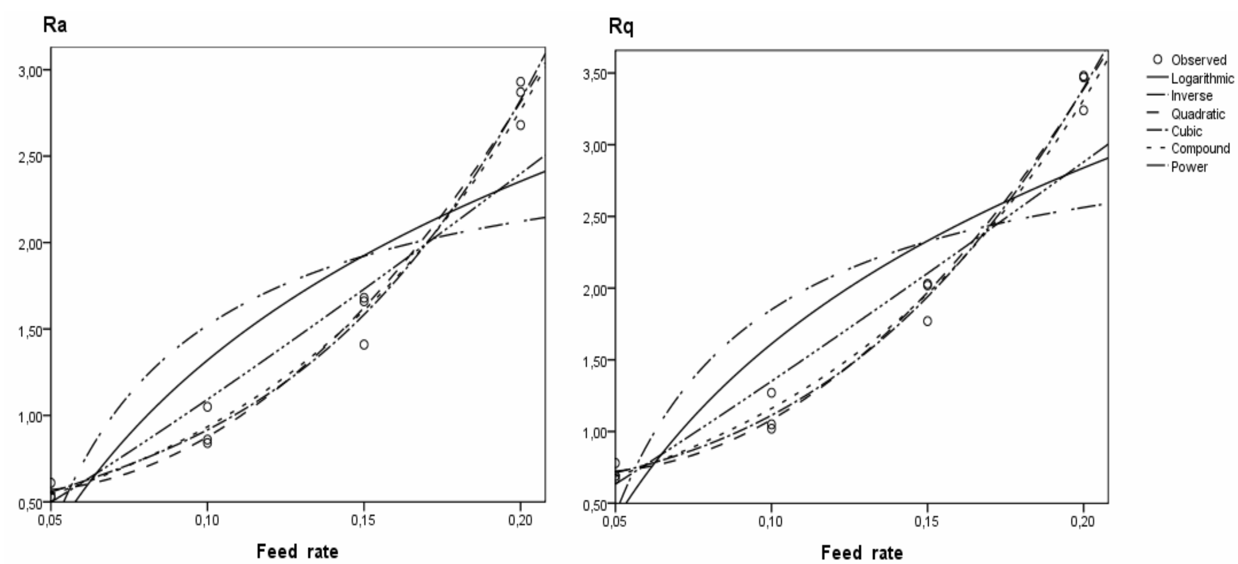

Figure 2. Ra and Rq as function of the feed rate for all non-linear regression models; PEEK CF30 using PCD tool

Power: $R_a = 14.89 f^{1.134}, \; R_q = 16.69 f^{1.092}$

Compound: $R_a = 0.316(51814)^f, \; R_q = 0.407(35949)^f$

The various mathematical models as determined by regression for Ra and Rq which are associated to PEEK GF30 cut with PCD tool:

Quadratic:

$$R_a = 0.897 - 7.14 f + 103.3 f^2, \; R_q = 1.142 - 8.487 f + 122 f^2$$

Cubic:

$$R_a = 1.667 - 31.63 f + 323.3 f^2 - 586.7 f^3, \; R_q = 2.11 - 39.29 f + 398.7 f^2 - 737.8 f^3$$

Inverse: $R_a = 3.505 - \frac{0.15}{f}, \; R_q = 4.208 - \frac{0.177}{f}$

Logarithmic:

$$R_a = 6.052 + 1.867 \ln(f), \; R_q = 7.208 + 2.198 \ln(f)$$

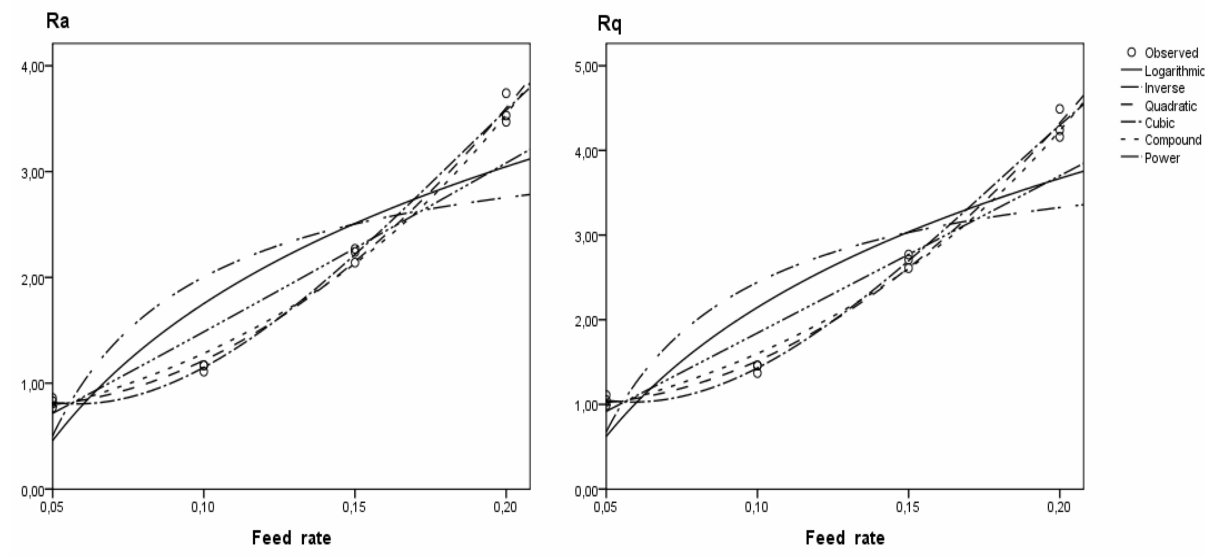

Figure 3. Ra and Rq as function of the feed rate for all non-linear regression models; PEEK GF30 using PCD tool.

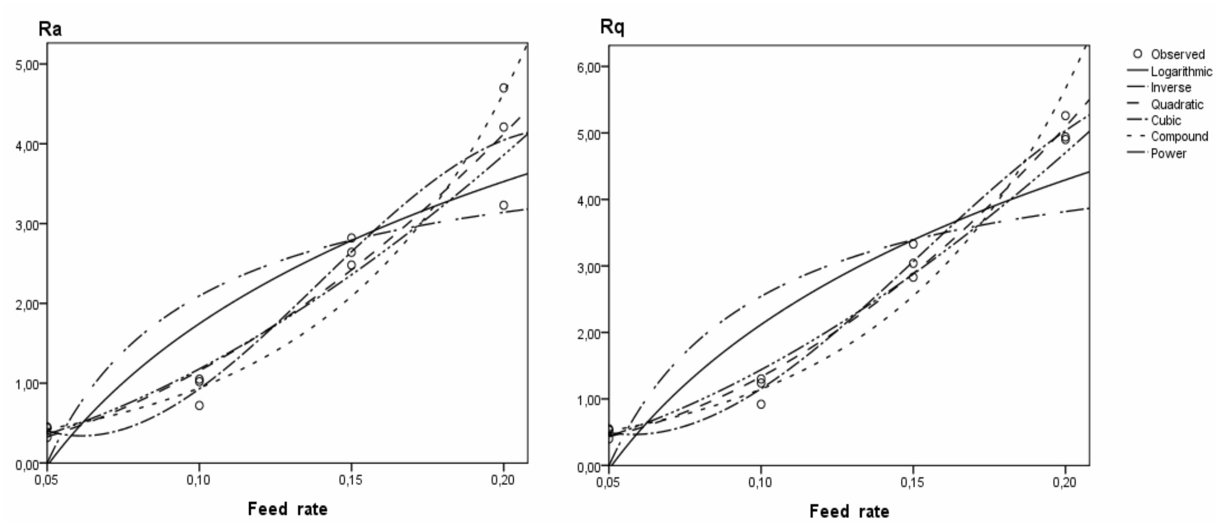

Figure 4. Ra and Rq as function of the feed rate for all non-linear regression models; PEEK using K10 tool.

Power: $R_a = 16.755\, f^{\,1.052}$, $R_q = 18.66\, f^{\,1.005}$

Compound:

$$R_a = 0.464(25811)^f \,, R_q = 0.605(16758)^f$$

The various mathematical models as determined by regression for Ra and Rq which are associated to PEEK cut with K10 tool:

Quadratic:

$$R_a = -0.063 + 3.46\,f + 87.33\,f^2 \,,\; R_q = 0.187 - 1.606\,f + 130.7\,f^2$$

Cubic:

$$R_a = 2.573 - 80.41f + 840.7f^2 - 2009f^3, R_q = 2.286 - 68.39f + 730.5f^2 - 1600f^3$$

Inverse: $R_a = 4.189 - \frac{0.209}{f}$, $R_q = 5.092 - \frac{0.255}{f}$

Logarithmic: $R_a = 7.661 + 2.569\ln(f)$, $R_q = 9.345 + 3.138\ln(f)$

Power: $R_a = 60.6\, f^{\,1.711}$, $R_q = 73.50\, f^{\,1.708}$

Compound:

$$R_a = 0.191(8452589)^f \,,\; R_q = 0.233(8588130)^f$$

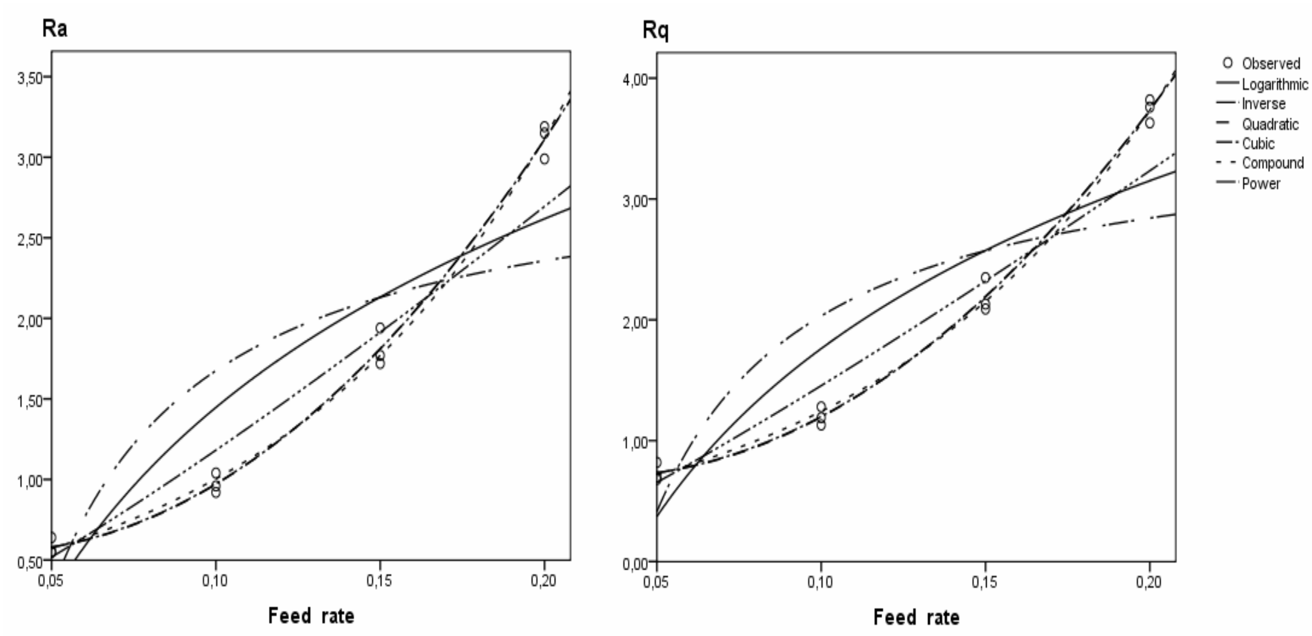

Figure 5. Ra and Rq as function of the feed rate for all non-linear regression models; PEEK CF30 using K10 tool.

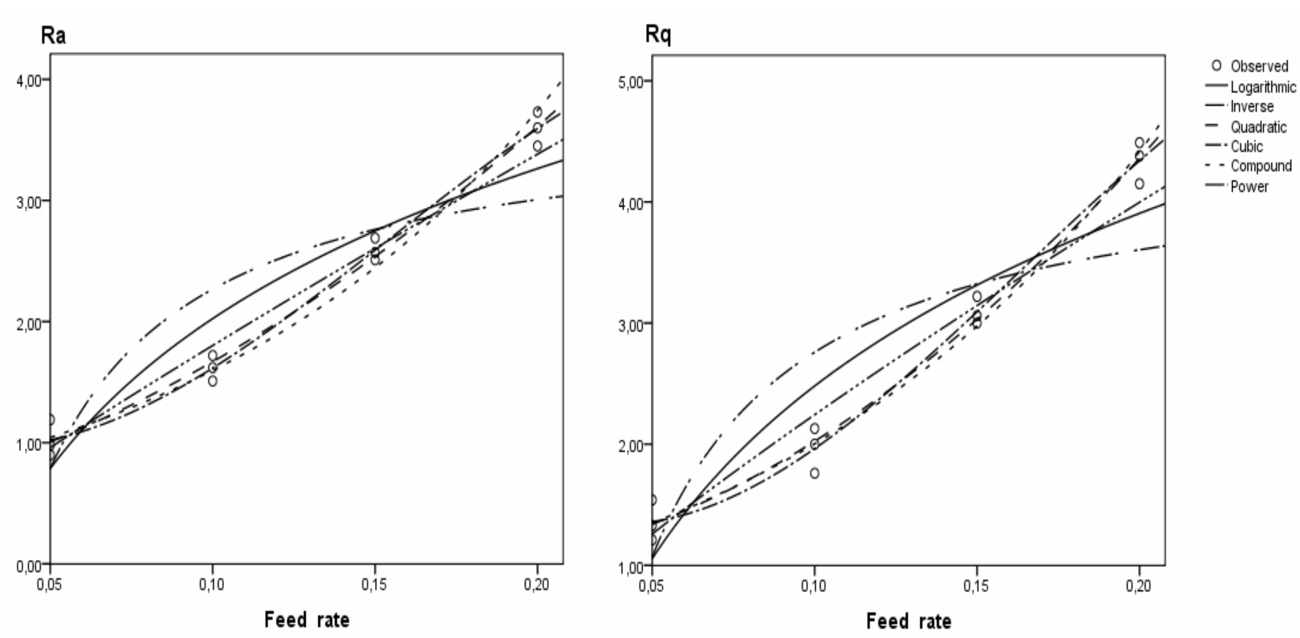

Figure 6. Ra and Rq as function of the feed rate for all non-linear regression models; PEEK GF30 using K10 tool.

The various mathematical models as determined by regression for Ra and Rq which are associated to PEEK CF30 cut with K10 tool:

Quadratic:

$$R_a = 0.645 - 0.813f + 90.67f^2, \; R_q = 0.815 - 7f + 108f^2$$

Cubic

$$R_a = 0.61 - 4.7f + 80.67f^2 - 26.67f^3, \; R_q = 0.757 - 5.144f + 91.33f^2 + 44.44f^3$$

Inverse:

$$R_a = 3.04 - \frac{0.136}{f}, \; R_q = 3.652 - \frac{0.162}{f}$$

Table 3. Sig and R^2 values for R_a models using PCD cutting tool

Models	Work material					
	PEEK		PEEK CF30		PEEK GF30	
	Sig	R^2	Sig	R^2	Sig	R^2
Logarithmic	0.000	0.790	0.000	0.798	0.000	0.811
Inverse	0.002	0.673	0.002	0.647	0.001	0.654
Quadratic	0.000	0.959	0.000	0.987	0.000	0.994
Cubic	0.000	0.968	0.000	0.988	0.000	0.996
Compound	0.000	0.968	0.000	0.984	0.000	0.984
Power	0.000	0.911	0.000	0.932	0.000	0.915

Table 4. Sig and R^2 values for R_q models using PCD cutting tool.

Models	Work material					
	PEEK		PEEK CF30		PEEK GF30	
	Sig	R^2	Sig	R^2	Sig	R^2
Logarithmic	0.000	0.790	0.000	0.798	0.000	0.810
Inverse	0.002	0.630	0.002	0.645	0.001	0.653
Quadratic	0.000	0.985	0.000	0.99	0.000	0.993
Cubic	0.000	0.991	0.000	0.99	0.000	0.996
Compound	0.000	0.971	0.000	0.983	0.000	0.981
Power	0.000	0.902	0.000	0.924	0.000	0.909

Table 5. Sig and R^2 values for R_a models using K10 cutting tool

Models	Work material					
	PEEK		PEEK CF30		PEEK GF30	
	Sig	R^2	Sig	R^2	Sig	R^2
Logarithmic	0.000	0.820	0.000	0.819	0.000	0.897
Inverse	0.001	0.681	0.001	0.668	0.000	0.769
Quadratic	0.000	0.939	0.000	0.995	0.000	0.988
Cubic	0.000	0.952	0.000	0.995	0.000	0.989
Compound	0.000	0.951	0.000	0.992	0.000	0.974
Power	0.000	0.950	0.000	0.947	0.000	0.960

Table 6. Sig and R^2 values for R_q models using K10 cutting tool

Models	Work material					
	PEEK		PEEK CF30		PEEK GF30	
	Sig	R^2	Sig	R^2	Sig	R^2
Logarithmic	0.000	0.843	0.000	0.819	0.000	0.873
Inverse	0.001	0.695	0.001	0.667	0.000	0.737
Quadratic	0.000	0.986	0.000	0.995	0.000	0.985
Cubic	0.000	0.992	0.000	0.995	0.000	0.987
Compound	0.000	0.970	0.000	0.991	0.000	0.974
Power	0.000	0.963	0.000	0.943	0.000	0.939

Logarithmic:

$$R_a = 5.336 + 1.689 \ln(f),\ R_q = 6.377 + 2.004 \ln(f)$$

Power:

$$R_a = 18.26 f^{1.189},\ R_q = 20.64 f^{1.152}$$

Compound:

$$R_a = 0.323(83280)^f,\ R_q = 0.414(59426)^f$$

The various mathematical models as determined by regression for Ra and Rq which are associated to PEEK GF30 cut with K10 tool:

Quadratic:

$$R_a = 0.547 + 7.117 f + 41 f^2,\ R_q = 0.976 + 4.057 f + 64.33 f^2$$

Cubic:

$$R_a = 1.16 - 12.37 f + 216 f^2 - 466.7 f^3,\ R_q = 1.693 - 18.77 f + 269.3 f^2$$

Inverse:

$$R_a = 3.748 - \frac{0.148}{f},\ R_q = 4.45 - \frac{0.169}{f}$$

Logarithmic:

$$R_a = 6.139 + 1.787 \ln(f),\ R_q = 7.216 + 2.056 \ln(f)$$

Power:

$$R_a = 14.59 f^{0.908},\ R_q = 15.27 f^{0.833}$$

Compound:

$$R_a = 0.681(5010)^f,\ R_q = 0.909(2706)^f$$

From these Figures, one could easily recognize that not the all proposed models are adequate for describing roughness parameters of PEEK machined by PCD tool. The logarithmic model for example is not good because its R^2 value is smaller than that of all the others. But generally, one could observe that the quadratic regression model, the cubic model and the compound model are the more suitable ones since their R^2 are maximal, it is interesting to note that the quadratic and cubic curves were similar in the Figure 5.

Table 3, respectively Table 4, give the significance and R square parameters for the various non-linear regression models associated to R_a , respectively to R_q, which were obtained in case of machining of PEEK composites by using cutting PCD tools.

Table 5, respectively Table 6, give the significance and

R square parameters for the various non-linear regression models associated to R_a , respectively to R_q, which were obtained in case of machining of PEEK composites by using cutting K10 tools.

From Table 3 to 6, one can notice that the most adequate non-linear regression models which best fit experimental measured roughness parameter R_a when machining PEEK composites using cutting tools, PCD and K10, are the quadratic, cubic and the compound models. For roughness parameter R_q, when the same conditions of machining are considered, the best regression models are again the quadratic, cubic and the compound ones, but the quadratic model is the easiest and most suitable to be used.

Conclusion

The following conclusions can be drawn from the results obtained in this study:

There exist non-linear relationships between the responses and the feed rate.

The quadratic, cubic and compound forms are the most adequate models which could be developed to give non-linear regressions for the two roughness parameters R_a and R_q.

The results are valid within the specified range experimental investigation of the feed rate parameter. Any extrapolation must be confirmed by further experiments.

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