Indian Journal of Engineering & Materials Sciences
Vol. 19, June 2012, pp. 163-174

Optimization of surface roughness in turning unidirectional glass fiber reinforced plastics (UD-GFRP) composites using polycrystalline diamond (PCD) cutting tool

Surinder Kumar[a]*, Meenu[a], P S Satsangi[b] & H K Sardana[c]

[a]Department of Mechanical Engineering, National Institute of Technology, Kurukshetra 136 119, India

[b]Department of Mechanical Engineering, PEC University of Technology, Chandigarh 160 012, India

[c]Department of Computational Instrumentation, CSIR-CSIO, Chandigarh 160 030, India

Received 1 November 2011; accepted 22 May 2012

Glass fiber reinforced plastic (GFRP) composite materials are a feasible alternative to engineering materials and are being extensively used in variety of engineering applications. Machining of unidirectional glass fiber reinforced plastic (UD-GFRP) composites is different from that of conventional materials and causes excessive tool wear. A study is conducted in the machining of unidirectional glass fiber reinforced plastic (UD-GFRP) composite material to investigate the effect of tool nose radius, tool rake angle, feed rate, cutting speed, depth of cut and along with cutting environment (dry, wet and cooled (5-7°C) temperature) on the surface roughness produced. The experimental results reveal that the most significant machining parameters for surface roughness is feed rate followed by cutting speed. Cutting environment does not influence the surface roughness significantly. The predicted values and measured values are in good agreement as observed by further confirmation experiments.

Keywords: UD-GFRP composites, Cutting parameters, Optimization, Machining, Response table, ANOVA, Surface roughness, Polycrystalline diamond (PCD) tool, Turning, Taguchi method

Fiber reinforced plastic composite (FRP) materials have been widely used in a variety of structures such as aircraft, robots and machines. An important aspect of production is machining. There is significant difference between the machining of conventional metals and their alloys and that of composite materials. This is because FRPs are anisotropic and inhomogeneous. Machining characteristics of composites vary from metals due to the following reasons: (i) FRP is machining in a limited range of temperature, (ii) the low thermal conductivity causes heat buildup in the cutting zone during machining operation, since here is only little dissipation by the materials, (iii) the difference in the coefficient of linear expansion between the matrix and the fiber gives rise to residual stresses and makes it difficult to attain high dimensional accuracy. In recent years, glass fiber reinforced plastics (GFRPs) have been extensively used in variety of engineering applications in different fields such as aerospace, oil, gas and process industries. GFRP composite components are normally fabricated by processes such as filament winding, hand lay-up, etc. After fabrication, they require further machining to facilitate dimensional control for easy assembly and for functional aspects. The machining of GFRP composites is different from conventional materials. Santhanakrishnan *et al*.[1] presented machinability study in turning process of GFRP, CFRP and Kevlar fiber reinforced plastics composite using P20 carbide, TiC coated carbide, K20 carbide and HSS tool. Three parameters such as cutting speed, feed rate and depth of cut were selected to minimize the surface roughness. Tangential cutting force, feed force and radial force were measured by using inductive type lath tool dynamometer. It was found that, the K20 carbide tool performed better in machining fiber reinforced plastics composites. Kevlar fiber reinforced plastics (KFRPs) machined surface exhibit poor surface finish due to the fussiness caused by delaminated, dislocated and strain ruptured tough Kevlar fibers[1]. The behaviour of composites is anistropic. The quality of machined products depends upon the fibers, matrix materials used, bond strength between fiber and matrix, type of weave etc. Unlike the machining of traditional materials, typical problems are encountered in the machining of FRP due to diverse fiber and matrix properties[1,2].

*Corresponding author (E-mail: surinder.asd@gmail.com)

Problems encountered are fibers pull out, short tool life, matrix debonding, burning and formation of powder like chips[3]. In machining of fiber reinforced composite materials, there are a number of problems associated. For example, the varying material properties and degrees of anisotropy cause difficulty in predicting the behaviour of the material being machined. This can lead to specific problems of FRP machining[4]. The machining of fiber-reinforced materials requires special considerations about the wear resistance of the tool. High speed steel (HSS) is not suitable for cutting owing to the high tool wear and poor surface finish. Hence, carbide and diamond tools are used as suitable cutting tool materials[5,6]. Palanikumar[7] worked on finding optimum cutting parameters for minimizing surface roughness using Taguchi's method. He mentioned the benefits of using Taguchi's method. It offers a simple and systematic approach to optimize design. By applying this technique, one can significantly reduce the number of experiments and time required for experimentation.

An *et al*.[8] investigated the machinability of glass fiber reinforced plastics by means of tool made of various materials and geometries. Three parameters such as cutting speed, feed rate and depth of cut were selected to minimize the surface roughness and cutting force. Single crystal diamond, poly crystal diamond and cubic boron nitride were used for turning process. It was found that, the single crystal diamond tool is excellent for GFRP cutting. Palanikumar *et al*.[9] investigate on focused on the multiple performance machining characteristics of GFRP composites using carbide (K10) tool. Five parameters such as work piece (fiber orientation), cutting speed, feed rate, depth of cut and machining time were selected to minimize the surface roughness. It was found that the machining performance in the composite machining process can be improved by including more number of parameters and levels.

Sreejith *et al*.[10] observed that the cutting force and the cutting temperature affect the performance of the cutting tools while machining carbon/carbon composites. Davim *et al*.[11] used a polycrystalline diamond (PCD) cutting tool to machine FRP tubes and obtained optimal cutting parameters for surface roughness. Davim *et al*.[12] investigated the machinability in turning process of glass fibers reinforced plastics (GFRP) using polycrystalline diamond and cemented carbide tool. Two parameters such as cutting speed and feed rate were selected to minimize the surface roughness and cutting force. It was found that, the polycrystalline diamond provide a better machinability index in comparison to cemented carbide tool (K15). Palanikumar[13] predicted and evaluated the surface roughness of GFRP workpiece using response surface method. Four parameters such as work piece (fiber orientation), depth of cut, feed rate and cutting speed were selected to minimize the surface roughness. Coated cermets tool was used for turning process. Hussan *et al*.[14] developed a surface roughness prediction model for the machining of GFRP pipes using response surface methodology by using carbide tool (K20). Four parameters such as cutting speed, feed rate, depth of cut and work piece (fiber orientation) were selected to minimize the surface roughness. It was found that, the depth of cut shows a minimum effect on surface roughness as compared to other parameters.

Palanikumar[15] evaluated the effect of cutting parameters on the surface roughness of the GFRP composites using PCD tool. Three parameters such as cutting speed, feed rate and depth of cut were selected to minimize the surface roughness. It was found that, for achieving good surface finish on the GFRP work piece, high cutting speed and high depth of cut. Depth of cut shows minimum effect on surface roughness compared to other parameters. Most of the studies on GFRP composites machining shows that minimizing the surface roughness is a serious task. In order to know surface quality and dimensional properties, it is necessary to employ theoretical model for prediction purpose. For prediction, the response surface methodology (RSM) is practical, economical and relatively easy to use[16]. Davim *et al*.[17] attempted to study the influence of cutting conditions on surface roughness during turning by design of experiments and regression analysis. Aravindan *et al*.[18] investigated the machinability of hand layup GFRP pipes using statistical techniques. Khan *et al*.[19] proposed an approach for turning of a glass fiber reinforced plastic composites using two different alumina cutting tools: namely, a Ti[C, N] mixed alumina cutting tool (CC650) and a SiC whisker reinforced alumina cutting tool (CC670). Three parameters such as cutting speed, depth of cut and feed rate were selected to minimize the surface roughness. It was found that the performance of the SiC whisker reinforced alumina cutting tool is better than that of the Ti[C, N] mixed alumina cutting tool for machining GFRP composite. Rajasekaran *et al*.[20]

used fuzzy logic for modeling and prediction of CFRP work piece. Three parameters such as depth of cut, feed rate and cutting speed were selected to minimize the surface roughness. Cubic boron nitride tool was used for turning process. It was found that the fuzzy logic modeling technique can be effectively used for the prediction of surface roughness in machining of CFRP composites.

Sakuma *et al.*[21] measured cutting resistance and surface roughness for analyzing the machinability and tool wear in face turning of glass fiber-reinforced plastics. They also studied the effect of fiber orientation on both the quality of the machined surface and tool wear. Ferreira *et al.*[22] observed the performance of different tool materials like ceramic, cemented carbide, Cubic boron nitride (CBN) and diamond while turning. Experimental results showed that only diamond tools are suitable for use in finish turning.

Spur and Wunsch[23] studied the turning of glass fiber reinforced (GFR) polyester and epoxy and found an increased surface roughness with increase in the feed rate but no dependence on the cutting velocity. Palanikumar *et al.*[24] investigated the turning process of the glass fiber reinforced plastics composite material with coated cermets tool and four parameters such as cutting speed, fiber orientation angle, depth of cut and feed rate were selected ranging from 75 to 175 rpm, 30 to 90 degree, 0.5 to 1.5 mm and feed rate from 0.10 to 0.50 mm/rev. It was observed that the feed rate is the factor, which has greater influence on surface roughness, followed by cutting speed. Palanikumar *et al.*[25] optimized the machining parameters in turning glass fiber reinforced plastics composites using carbide (K10) tool. Five parameters such as work piece (fiber orientation), cutting speed, feed rate, depth of cut and machining time were selected to minimize the surface roughnss. Taguchi's technique with fuzzy logic was used. Authors concluded that, technique is more convenient and economical to predict the optimal machining parameters. Sait *et al.*[26] presented an influence of machining parameters on surface roughness of GFRP pipes using coated carbide (K20) tool. Three parameters such as cutting speed, feed rate and depth of cut were selected to minimize the surface roughness. It was found that the quality of the machined surface of filament wound GFRP pipes is better than the hand layup GFRP pipes. Hussain *et al.*[27] developed a surface roughness and cutting force prediction model for the machining of GFRP tubes using response surface methodology by using carbide tool (K20), cubic boron nitride (CBN) and polycrystalline diamond (PCD). Four parameters such as cutting speed, feed rate, depth of cut and work piece (fiber orientation) were selected to minimize the surface roughness and cutting force. It was found that, the polycrystalline diamond (PCD) cutting tool is better. The surface roughness increased more rapidly after 30° fiber orientation. At larger fiber angles, compressive strain is generated within the work material. This resulted in larger surface roughness[27]. It is known that the mechanism of cutting in GFRP composites is due to the combination of plastic deformation, shearing and bending rupture. The occurrence of the above mechanisms depends on the flexibility, orientation and toughness of the fibers. These constitute a surface texture on the work-piece[28]. The high mechanical resistance of fibers is the reason for an excessive wear down of cutting tool and a great damage in the polymeric matrix, since the fibers are taken of the matrix. In general, a cutting tool fails by gradual wear or by fracturing. The degree of tool wear influences the surface quality. In addition to the roughness, which results from the transferring of the cutting edge corner on the work-piece surface in relation to feed rate and tool geometry, rising values of roughness occur with increasing width of flank wear land[29].

Bagci and Isik[30] investigated the turning of UD-GFRP material. In their study, an artificial neural network and response surface model based on experimental measurement data was developed to estimate surface roughness in orthogonal cutting of GFRP. Hussain *et al.*[31] developed a surface roughness prediction model for the machining of GFRP tubes using fuzzy model by using carbide tool (K20). Four parameters such as cutting speed, feed rate, depth of cut and work-piece (fiber orientation) were selected to minimize the surface roughness. It was observed that the model can be effectively used for predicting the surface roughness (R_a) in turning of GFRP composites.

GFRP is a cheaper option than carbon or Kevlar, so GFRP rods were used in this work. Advantages of GFRP are[32]: more compatible with resin and timber, high resistance to corrosion, useful in a humid or acid environment, improved performance due to better resin bonding, more light weight connection, hence easier handling. In this paper Taugchi's DOE approach is used to analyze the effect of turning process parameters – tool nose radius, tool rake angle, feed rate, cutting speed, cutting environment (dry, wet and cooled) and depth of cut on the surface roughness by using PCD inserts on UD-GFRP and optimal setting of these parameters is found that may result in minimizing surface roughness.

Taguchi Method Application for Turning Operation

The implication of fundamental knowledge of the turning process for applying the Taguchi method to this problem warrants a review of past studies involving machining parameters and conditions and their effect on surface roughness. Feng *et al.*[33] found that many published studies include spindle speed and feed rate and a few included the depth of cut. Decreased feed rate has been found to generally reduce surface roughness. However, the effects of the spindle speed and depth of cut on surface roughness seem to have different interpretations[33,34]. Numerous studies have been conducted on the subject of parameter optimization of turning operations, each focusing on a specific methodology and parameters. There are some excellent examples of reported studies which have been conducted using the Taguchi method for the purpose of optimizing turning parameters.

Experimental Procedures

Materials and Method

In the present study, Pultrusion processed unidirectional glass fiber reinforced plastic composite rods are used. Pultrusion process is an effective method to manufacture strong light weight composite materials. Fibers are pulled from spools through a device that coats them with a resin. They are then typically heat treated and cut to length. The word Pultrusion describes the method of moving the fibers through the machinery. The diameter of the rod taken is 42 mm and length 840 mm. The fiber used in the rod is E-glass and resin used is epoxy. Figure 1 shows the specimen used for experimentation and properties of material are given in Table 1. The first step in Taguchi method is to determine the quality characteristic which is to be optimized. In this study, a surface roughness is the quality characteristics. In the second step, the control parameters or test parameters which have significant effects on the quality characteristics are identified with the required number of levels. In the third step, the appropriate orthogonal array for the control parameters is selected after calculating the minimum number of experiments required to be conducted by considering the interactive effects. Taguchi categorized the performance characteristics of a system into three different kinds based on the type of performance: the nominal the best, the smaller the better, and the larger the better. In this study, smaller the better principle is considered as surface roughness is to be minimized. The corresponding loss function can be expressed as follows:

Fig. 1– UD- GFRP composite rod specimens

Smaller the best characteristics:

$$S/N = -10 \log \frac{1}{n} \Sigma y^2 \quad \ldots (1)$$

Where y is the observed data and n is number of observations

Table 1—Mechanical and thermal properties of the UD-GFRP material

Sr.	Particular	Value	Unit
1	Glass content (by weight)	75±5	%
2	Epoxy resin content (by weight)	25±5	%
3	Reinforcement, unidirectional	'E' Glass roving	%
4	Water absorption	0.07	%
5	Density	1.95-2.1	g/cc
6	Tensile strength	6500	kg/cm^2
7	Compression strength	6000	kg/cm^2
8	Shear strength	255 kgf	kg/cm^2
9	Modulus of elasticity	3200	10 kg/cm^2
10	Thermal conductivity	0.30	kcal/MhºC
11	Weight of rod 840 mm	2.300	kg
12	Electrical strength (radial)	3.5	kV/mm
13	Working temperature class	Class 'F' (155)	centigrate
14	Martens heat distortion temperature	210	centigrate
15	Test in oil : (1) at 20°C (2) at 100°C	20 kC/cm 20 kC/cm (50 kC/ 25 mm)	kV/cm

Experimental set-up

The experiments were conducted on a NH22 lathe machine with the following specifications**:** a height of center 220 mm, swing over bed 500 mm, spindle speed range 60-3000 rpm, feed range 0.04-2.24 mm/rev and main motor 11 kW. The machining tests were carried out dry, wet and cooled (using water-soluble cutting fluid). Sufficient care was taken to remove the highly abrasive UD-GFRP machining chips by directing the coolant on the rod. A tool holder SVJCR steel EN47 was used during the turning operation**.** The geometries of the cutting tool used are given in Table 2. The surface roughness was measured by using Tokyo Seimitsu Surfcom 130A type instrument as shown in Fig. 2. The Taguchi's approach to experiment design is described in the flow chart shown in Fig. 3.

Taguchi method based experiment plan

The experiments for this work were planned using Taguchi's design of experiments (DoE). Taguchi's approach to parameter design provides the design engineer with a systematic and efficient method for determining near optimum design parameters for performance and cost[35]. This method can dramatically reduce the number of experiments required to gather necessary data. For the experimental plan, the Taguchi's mixed level design was selected as it was decided to keep two levels of tool nose radius. The rest five parameters were studied at three levels. Two level parameter has 1 DOF, and the remaining five three level parameters have 10 DOF, i.e. the total DOF required will be 11 [= (1*1+ (5*2)]. The most appropriate orthogonal array in this case is L_{18} (2^1 * 3^7) OA with 17 [= 18-1] DOF. Standard L_{18} OA with the parameters assigned by using linear graphs is used. The unassigned columns will be treated as error. According to the Taguchi design concept, a L_{18} orthogonal array was chosen for the experiments as shown in Table 3. The L_{18} orthogonal array has 18 rows corresponding to the number of tests. The parameters tool nose radius, tool rake angle, feed rate, cutting speed, cutting environment and depth of cut are assigned to columns (A, B, C, D, E, F) respectively as shown in Table 3. Out of which cutting environment parameters (dry, wet and cooled) were especially applied to composite rods. The cutting environment (dry, wet and cooled) on the work-piece was set during the machining of the rod, so as to get a comparative assessment of the performance of cutting environment which has not been studied earlier. The output responses used to measure the machinability are surface roughness. The parameters selected, the designated symbols, and their ranges are given in Table 4. The analysis was made using the popular software, specifically used for design of experiment applications, known as MINITAB 15.

Table 2– Tool geometries

Clearance angle	7º
Grade	M10
Cutting edge inclination angle top clearance	7º
Front clearance	10º
Tool nose radius	0.4 and 0.8 mm
Tool rake angles	-6º, 0º, +6º and -6º, 0º, +6º

Fig. 2– Surface roughness tester

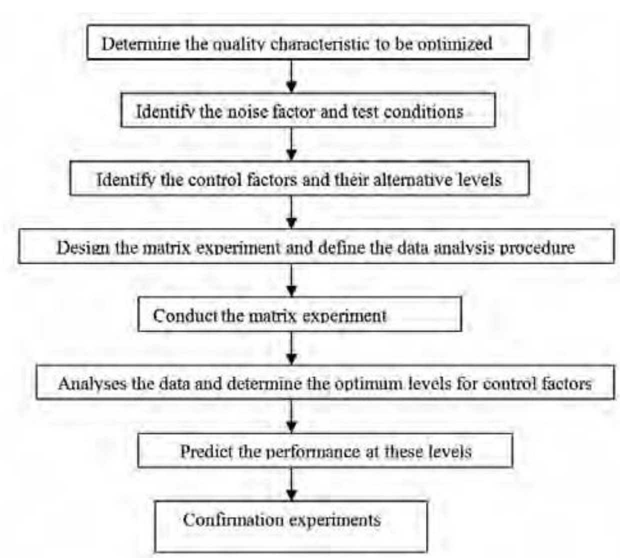

Fig. 3– Flow chart for DOE

Table 3– Experimental layout using L_{18} orthogonal array

Expt. No.	A	B	C	D	E	F	---	---
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

For example, for trial no. 1, the S/N ratio is:

$$S/N = -10 \log [1/3\,(1.38^2 + 1.46^2 + 1.35^2)] = -2.90665 \quad \ldots (2)$$

The values of the variables required for the calculation of the total variation is taken from Table 5.

Variation due to error (SSe)

$$SSe = SST - [SS_A + SS_B + SS_C + SS_D + SS_E + SS_F] = 2.95649$$

The degree of freedom for the error (v_e) is:

$$v_e = v_T - [v_{A+} v_B + v_C + v_D + v_E + v_F + v_e] = 53-[1+2+2+2+2+2] = 42$$

Where v_T is the total degree of freedom.

The percent contribution is the portion of the total variation observed in an experiment attributed to each significant factor which is reflected. The percent contribution is a function of the sums of squares for

Table 4—Control parameters and their levels

Process parameters design	Process parameters	Levels		
		Low (1)	Medium (2)	High (3)
A	Tool nose radius, mm	0.4	0.8	NIL
B	Tool rake angle, degree	-6	0	+6
C	Feed rate, mm/rev	0.05	0.1	0.2
D	Cutting speed, m/min & rpm	(55.42) 420	(110.84) 840	(159.66) 1210
E	Cutting environment	Dry (1)	Wet (2)	Cooled (3)
F	Depth of cut, mm	0.2	0.8	1.4

Table 5– Test data summary for surface roughness

Expt. No.	Ra_1	Ra_2	Ra_3	Average response on surface roughness, R_a/μm	S/N ratio (dB)
1	1.38	1.46	1.35	1.397	-2.90665
2	1.67	4.36	1.33	1.453	-3.29561
3	3.00	2.79	3.44	3.076	-9.79513
4	1.31	1.47	1.32	1.366	-2.72569
5	1.70	1.24	1.65	1.53	-3.77191
6	2.05	2.93	2.22	2.40	-7.71240
7	1.61	1.33	1.60	1.513	-3.63048
8	1.67	1.79	1.45	1.636	-4.31122
9	2.43	2.20	2.16	2.263	-7.10695
10	1.38	183	1.43	1.547	-3.86095
11	1.52	1.43	1.87	1.606	-4.17870
12	2.24	1.90	1.76	1.966	-5.91999
13	1.57	1.57	1.65	1.597	-4.06671
14	1.40	1.86	1.63	1.63	-4.30102
15	2.14	1.80	2.77	2.237	-7.13000
16	2.12	1.80	1.90	1.940	-5.77660
17	1.23	1.53	1.70	1.486	-3.51783
18	1.98	1.66	2.28	1.973	-5.97490
Average				$\bar{T}_{Ra} = 1.812$	-4.999

each significant item. It indicates the relative power of a factor to reduce the variation. If the factor levels were controlled precisely, then the total variation could be reduced by the amount indicated by the percent contribution. The variation due to a factor contains some amount due to error; it is represented by the following form for factor A given below:

Variance (V) = (SS_A/DOF)

F_{ratio} = (V/error)

Percent contribution $SS'_A = SS_A - (V_e \times V_A)$

Table 5 test data summary shows the experimental results for surface roughness and their S/N ratios based on the experimental parameter combinations given in Table 3 for the eighteen (18) trial conditions. The minimum surface roughness of 1.366 µm was achieved in trial 4 at tool nose radius of 0.4 mm, tool rake angle of 0°, feed rate of 0.05 mm/rev, cutting speed of (55.42) m/min, wet cutting environment and depth of cut of 0.8 mm. Generally, at the combination of lowest level of tool nose radius, moderate tool rake angle, lowest feed rate, lowest cutting speed, moderate cutting environment (wet) and moderate depth of cut resulted in better surface roughness. The largest surface roughness (Ra) of 3.076 µm was obtained with trial 3, at the lowest tool nose radius (0.4 mm), lowest tool rake angle of (-6°), largest feed rate (0.2 mm/rev), largest cutting speed (159.66 m/min.), largest cutting environment (cooled) and the largest depth of cut (1.4 mm).

Results and Discussion

Analysis of variance

The analysis was performed using a statistical package, Minitab-15, to quantify the effect of the machining factors on the responses. For analyzing the significant effect of the parameters on the quality characteristics, F and P test is used. This analysis was

Table 6– Pooled ANOVA (raw data: surface roughness)

Source	SS	DOF	V	F ratio	Prob.	SS/	P (%)
Tool nose radius (A)	0.07114	1	0.07114	Pooled	0.321	—	—
Tool rake angle (B)	0.02324	2	0.01162	Pooled	0848	—	—
Feed rate (C)	6.94648	2	3.47324	49.34*	0.000	6.806	54.399
Cutting speed (D)	1.40654	2	0.70327	9.99*	0.000	1.266	10.119
Cutting Environment (E)	0.29613	2	0.14807	Pooled	0.135	—	—
Depth of cut (F)	0.81130	2	0.40565	5.76*	0.006	0.670	5.355
T	12.51133	53				12.51133	100.00
e (pooled)	2.95649	42	0.07039			3.731	29.821

SS = sum of squares, DOF = degrees of freedom, variance (V) = (SS/DOF), T = total, SS/ = pure sum of squares, P = percent contribution, e = error, F_{ratio} = (V/error), Tabulated F-ratio at 95% confidence level $F_{0.05;\,1;\,42} = 4.08$, $F_{0.05;\,2;\,42} = 3.23$, * Significant at 95% confidence level.

Table 7– S/N Pooled ANOVA (raw data: surface roughness)

Source	SS	DOF	V	F ratio	Prob.	SS/	P (%)
Tool nose radius (A)	0.0156	1	0.0156	Pooled	0.859	—	—
Tool rake angle (B)	0.0314	2	0.0157	Pooled	0.966	—	—
Feed rate (C)	46.5614	2	23.2807	51.09*	0.000	45.65	71.808
Cutting speed (D)	8.3717	2	4.1858	9.19*	0.015	7.460	11.735
Cutting Environment (E)	1.1464	2	0.5732	Pooled	0.350	—	—
Depth of cut (F)	4.7120	2	2.3560	5.17*	0.050	3.801	5.979
T	63.5727	17				63.5727	100.00
e (pooled)	2.7343	6	0.4557			7.747	12.186

Tabulated F-ratio at 95% confidence level $F_{0.05;\,1;\,6} = 5.99$, $F_{0.05;\,2;\,6} = 5.14$

carried out for a level of significance of 5%, i.e., for a level of confidence of 95% as shown in Table 6. From the ANOVA result, it is concluded that C–feed rate, D–cutting speed and F-depth of cut, have significant effect on surface roughness while A, B and E have no effect at 95% confidence level. It is found that feed rate is more significant factor than other parameters, whilst depth of cut is the least significant parameter. The surface roughness produced on the UD-GFRP work-piece is mainly due to the feed rate. The pooled ANOVA of the raw data (surface roughness) is given in Table 6 and the S/N ANOVA (pooled version) is given in Table 7. The percent contributions of parameters as quantified under column P of Tables 6 and 7 reveal that the influence of feed rate in affecting surface roughness is significantly larger than the cutting speed and depth of cut. The percent contributions of feed rate (54.399%), cutting speed (10.119%) and depth of cut (5.355%) in affecting the variation of surface roughness are significantly larger (95% confidence level) as compared to the contribution of the other parameters as shown in Table 6.

Analysis of the signal-to-noise ratio

Signal-to-noise ratio is utilized to measure the deviation of quality characteristic from the target. In this experiment, the response is the surface roughness which should be minimized, so the desired signal-to-noise ratio characteristic is in the category of smaller the better. Table 8 shows the signal-to-noise ratio of the surface roughness for each level of the factors. The difference of signal-to-noise ratio between level 1 and 3 indicates that feed rate contributes the highest effect ($\Delta_{max\text{-}min}$ = 3.445) on the surface roughness followed by cutting speed ($\Delta_{max\text{-}min}$ = 1.516) and depth of cut ($\Delta_{max\text{-}min}$ = 1.170). Also, signal-to-noise ratio is utilized to measure the deviation of quality characteristic from the target. On the other hand, the response table for average surface roughness is shown in Table 9 and confirms the results from the response table for signal-to-noise ratio. The response (S/N ratios and surface roughness) of various parameters at different levels are reported in Tables 8 and 9 respectively.

Analysis of the influence of machining parameters on surface roughness has been performed using response table, which indicates the response at each level of control factors. Response tables are used to simplify the calculations needed to analyze the experimental data. The difference of a factor on a response variable is the change in the response when the factor goes from its level 1 to level 3. The mean response refers to the average value of the performance characteristic for each parameter at different levels. The influence of each machining parameter can be more clearly presented by means of a response graph. The response graph shows the change in the response when the factor goes from its level 1 to level 3. The graph for surface roughness raw data and S/N ratios are presented in Figs 4a-4f. Figures 4a-4f show the effect of tool nose radius, tool rake angle, feed rate, cutting speed, cutting environment (dry, wet and cooled) and depth of cut on surface roughness in turning of UD-GFRP

Table 8– Response table for surface roughness (S/N ratio) at different factor levels

	Nose radius (A)	Tool rake angle (B)	Feed rate (C)	Cutting speed (D)	Cutting environment (E)	Depth of cut (F)
Level 1	-5.028	-4.993	-3.828	-4.594	-4.784	-4.739
Level 2	-4.970	-4.951	-3.896	-4.443	-4.860	-4.544
Level 3	—	-5.053	-7.273	-5.960	-5.353	-5.714
Differences (Δ)	0.059	0.102	3.445	1.516	0.569	1.170

Table 9– Response table for surface roughness (mean) at different factor levels

	Nose radius (A)	Tool rake angle (B)	Feed rate (C)	Cutting speed (D)	Cutting environment (E)	Depth of cut (F)
Level 1	1.849	1.841	1.560	1.726	1.753	1.747
Level 2	1.776	1.793	1.557	1.672	1.767	1.706
Level 3	—	1.802	2.319	2.038	1.917	1.984
Differences (Δ)	0.073	0.048	0.762	0.366	0.163	0.278

composites. The results indicated that the increase of tool nose radius reduce the surface roughness up to 0.8 mm as shown in Fig. 4a. The surface roughness increased with increase in tool rake angle as shown in Fig. 4b. The figure indicates that the surface roughness increased at higher feed rates and cutting speed as shown in Figs 4c and 4d**.** The reason being, the increase in the feed rate increases the heat generation and hence, tool wear, which resulted in the higher surface roughness. The increase in the feed rate also increases the chatter and it produces incomplete machining at faster traverse, which leads to higher surface roughness. At higher cutting speed debonding and fiber breakage are the reasons for poor surface roughness. The results indicated that the surface roughness increases with increase in cutting environment and depth of cut and is presented in Figs 4e and 4f. Based on the response graph and response table, the optimal machining parameters for the UD-GFRP machining process is achieved for the minimum value of surface roughness. The optimal conditions for the surface roughness are: (i) tool nose radius at level 2 (0.8 mm), (ii) tool rake angle at level 2 (0°), (iii) feed rate at level 2 (0.1 mm/rev),

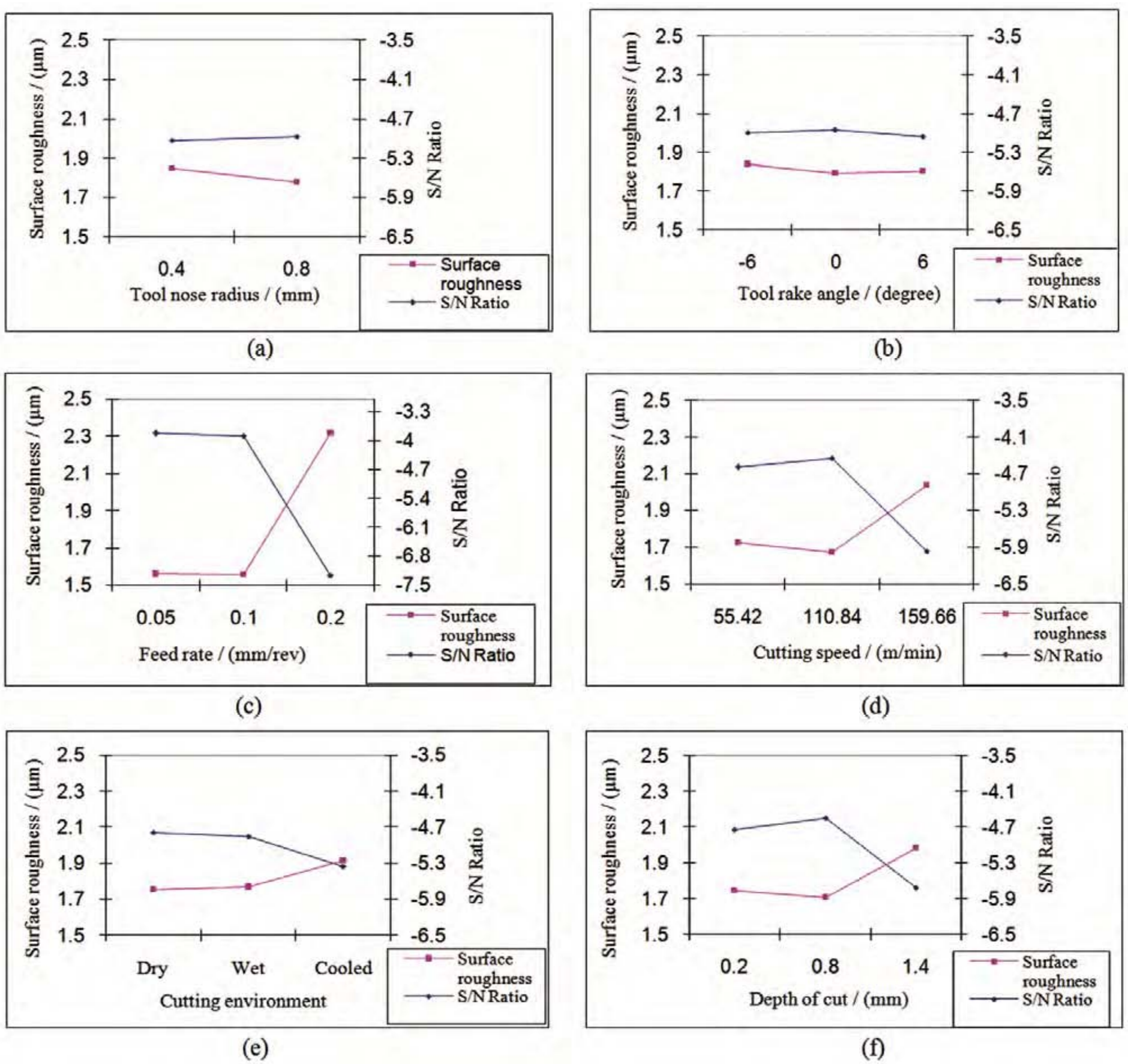

Fig. 4– Response and S/N ratio (a) effect of tool rake angle, (b) effect of tool nose radius, (c) effect of feed rate, (d) effect of cutting speed, (e) effect of cutting environment (dry, wet, cooled) and (f) effect of depth of cut

(iv) cutting speed at level 2 (110.84 m/min), (v) cutting environment at level 1 (dry) and (vi) depth of cut at level 2 (0.8 mm). Also residual plots for machining parameters (i) normal probability plot of residuals for surface roughness data, (ii) residuals vs. the order of the data, (iii) plot of residuals vs. the fitted values for surface roughness and (iv) histograms are shown in Fig. 5. It can be seen in Fig. 5a that all the points on the normal plot lie close to the straight line (mean line). This implies that the data are fairly normal and a little deviation from the normality is observed. It is noticed that the residuals fall on a straight line, which implies that errors are normally distributed. In addition, Figs 5b, 5c and 5d revealed that there is no noticeable pattern or unusual structure present in the data.

Estimation of optimum value of surface roughness

The purpose of the confirmation experiment in this study was to validate the optimum cutting conditions ($C_2D_2F_2$) that was suggested by the experiment and corresponded with the predicted values of average surface roughness.

The optimum conditions are set for the significant factors and the insignificant factors are set at economic level. Selected numbers of tests are run under constant specified conditions. The average of the results of the confirmation experiment is compared with the anticipated average based on the parameters and levels tested. The confirmation experiment is a crucial step and is highly recommended by Taguchi to verify the experimental conclusions[36]. The parameters and their selected levels are given in Table 10. Three confirmation experiments are conducted at the optimal settings of the turning process parameters recommended by the investigation. In this study, the confirmation runs with the optimum cutting condition $C_2D_2F_2$ resulted in response values of 1.571 μm, 1.340 μm and 1.443 μm. Each R_a measurement was repeated at least three times. Therefore, the optimum surface roughness (R_a = 1.451 μm) can be obtained under the earlier-mentioned cutting condition in the lathe machine.

The estimate of the mean (μ) is only a point estimate based on the average of the results obtained

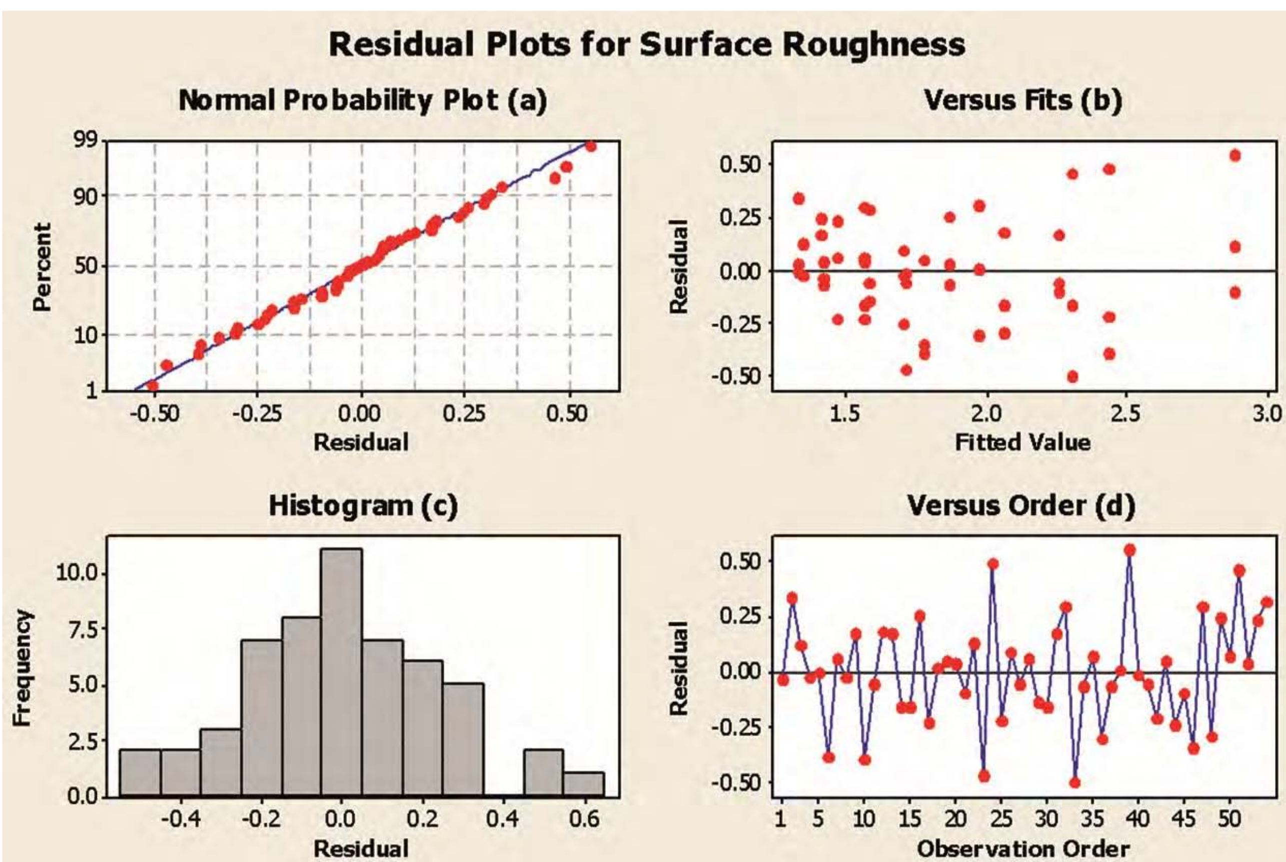

Fig 5– Residual plots for machining parameters (a) normal probability plot of residuals for surface roughness data, (b) plot of residuals vs. fitted values for surface roughness, (c) plot of residuals vs. the histogram and (d) residuals vs. the order of the data

Table 10– Parameters and their selected levels (for optimal surface roughness)

A	Tool nose radius	0.8 mm (the insignificant factor are set at economic levels)
B	Tool rake angle	0 degree (the insignificant factor are set at economic levels)
C	Feed rate	0.1 mm/rev
D	Cutting speed	110.84 m/min & 840 rpm
E	Cutting environment	Wet (the insignificant factor are set at economic levels)
F	Depth of cut	0.8 mm

from the experiment. Statistically, this provides a 50% chance of the true average being greater than μ and a 50% chance of the true average being less than μ. The confidence level is the maximum and minimum value between which the true average should fall at some stated percentage of confidence. The optimal surface roughness (μ_{Ra}) is predicted at the selected optimal setting of process parameters. The significant parameters with optimal levels are already selected as: C2, D2 and F2. The estimated mean of the response characteristic can be computed as[36].

$$\mu_{Ra} = \overline{T}_{Ra} + (\overline{C2} - \overline{T}_{Ra}) + (\overline{D2} - \overline{T}_{Ra}) + (\overline{F2} - \overline{T}_{Ra}) \quad \ldots (3)$$

Where $\overline{T}_{Ra}$ = overall mean of surface roughness = 1.812 μm (Table 5)

$\overline{C2}$, $\overline{D2}$ and $\overline{F2}$ are the mean values of surface roughness with parameters at optimum levels. From Fig. 4, $\overline{C2}$ =1.557 μm, $\overline{D2}$ =1.672 μm, $\overline{F2}$ =1.706 μm. Hence μ_{Ra} = 1.311 μm. A confidence interval for the predicted mean on a confirmation run can be calculated using the Eq. (4)[36]:

$$CI = (F\alpha \,;\, (1, f_e)\, V_e\, [1/n_{eff} + 1/R])^{½} \quad \ldots (4)$$

Where $F\alpha$; $(1, f_e) = F_{0.05}$; (1; 42) = 4.08 (tabulated).

α = risk = 0·05,

f_e = error DOF = 42 (Table 6)

N = total number of experiments = 18

V_e = error variance = 0.07039 (table 6)

Total DOF associated with the mean (μ_{Ra}) = 11, Total trial =18, N=18×3 = 54,

n_{eff} = effective number of replications

= N/{1+[Total DOF associated in the estimate of mean]}= 54 / (1 + 11) = 4.5

R = number of repetitions for confirmation experiment = 3

A =confidence interval for the predicted mean on a confirmation run is ± 0.399 using the Eq. (4).

The 95% confidence interval of the predicted optimal surface roughness is: $[\mu_{Ra} - CI] < \mu_{Ra} < [\mu_{Ra} + CI]$, i.e., $0.912 < \mu_{Ra}$ (μm) < 1.710

Confirmation Experiments

The average value of surface roughness while, turning UD-GFRP with PCD inserts is found to be 1.451 μm. This result is within the 95% confidence interval of the predicted optimal value of the selected machining characteristic (surface roughness). Hence, the optimal settings of the process parameters, as predicted in the analysis, can be implemented. Shows the conformance of results obtained in ANOVA as well as the results obtained using confirmation.

Conclusions

(i) The percent contributions of feed rate (71.808%), cutting speed (11.735%) and depth of cut (5.979%) in affecting the variation of surface roughness are significantly large (95 % confidence level) as compared to the contribution of the tool rake angle.

(ii) Feed rate is the factor, which has great influence on surface roughness, followed by cutting speed.

(iii) From the ANOVA result, it is concluded that C – feed rate, D – cutting speed, F – Depth of cut, have significant effect on surface roughness. A, B and E have no effect at 95% confidence level. It is found that feed rate is more significant factor than other parameters, whilst depth of cut is the least significant parameter.

(iv) Cutting environment does not influence the surface roughness significantly.

(v) The predicted range of the optimal surface roughness is: $0.912 < \mu_{Ra}$ (μm) < 1.710

References

1 Santhanakrishnan G, Krishnamurthy R & Malhotra S K, *Wear*, 132 (1989) 327-336.

2 Santhanakrishnan G, Krishnamurthy R & Malhotra S K, *J Mech Work Technol,* 17 (1988) 195-204.

3 Evestine G C & Rogers T G, *J Comp Mater,* 5 (1971) 94-105.

4 Konig W, Wulf Ch, Grab & Willerscheid H, *CIRP Ann,* 34 (1985) 537-548.

5 Davim J P & Reis P, *Int J Manuf Technol Manage*, 6(1/2) (2004) 185-197.

6 Sreejith P S, Krishnamoorthy R, Narayanasamy K & Malhotra S K, *J Mater Process Technol*, 88 (1999) 43-50.

7 Palanikumar K, *J Reinf Plast Compos,* 25 (2006) 1739-1751.

8 An S O, Lee E S & Noh S L, *J Mater Process Technol,* 68 (1997) 60-67.

9 Palanikumar K, Karunamoorthy L & Karthikeyan R, *Mater Manuf Process,* 21 (2006) 846-852.

10 Sreejith P S, Krishnamoorthy R & Malhotra S K, *J Mater Process Technol*, 183 (2007) 88-95.

11 Davim J P & Mata F, *Int J Adv Manuf Technol*, 26 (2005) 319-323.

12 Davim J P & Mata F, *Mater Des*, 28 (2007) 1050-1054.

13 Palanikumar K, *Mater Des*, 28 (2007) 2611-2618.

14 Hussain S A, Pandurangadu V & Palanikumar K, *Eur J Sci Res*, 41(1) (2010) 84-98.

15 Palanikumar K, *Int J Adv Manuf Technol,* 36 (2008) 19-27.

16 Yusuf Sahin & Riza Motorcu A, *Am J Appl Sci*, 1(1) (2004) 12-17.

17 Davim J P, *J Mater Process Technol*, 116 (2001) 305-308.

18 Aravindan S, Naveen Sait A & Noorul Haq A, *Int J Adv Manuf Technol*, 37 (2008) 1069-1081.

19 Khan M & Adam Kumar A, *J Manuf Process*, 13 (2011) 67–73.

20 Rajasekaran T, Palanikumar K & Vinayagam B K, *Prod Eng Res Dev*, 5 (2011) 191-199.

21 Sakuma By Keizo & Seto Masafumi, *Bull JSME*, 26(218) (1983) 1420-1427.

22 Fereirra J R, Coppini N L & Levy Neto, *J Mater Process Technol*, 109 (2001) 65-71.

23 Spur G & Wunsch U E, *Manuf Rev*, 1(2) (1988) 24-129.

24 Palanikumar K, Karunamoorthy L & Karthikeyan R, *Mater Des*, 27 (2006) 862-871.

25 Palanikumar K, Karunamoorthy L, Karthikeyan R & Latha B, *Met Mater Int*, 12(6) (2006) 483-491.

26 Naveen Sait A, Aravindan S & Noorul Haq A, *Adv Prod Eng Manage*, 4 (2009) 47-58.

27 Hussain S A, Pandurangadu V & Palanikumar K, *Int J Eng Sci Technol,* 4 (2011) 103-118

28 Santhanakrishnan G, *Investigations on machining of FRP composites and their tribological behaviour*, Ph.D. Thesis, IIT Madras, Chennai, India; 1990**.**

29 Jahanmir S, Ramulu M & Koshy, *Machining of Ceramics and Composites* (Dekker, New York, NY)*,* 1998, 238-243.

30 Bagci E, & Işık B, *Int J Adv Manuf Technol,* 31 (2006) 10-17.

31 Hussain S A, Pandurangadu V, Palanikumar K & Bharathi V V, *Jordan J Mech Ind Eng*, 5(5) (2011) 433-438

32 Harvey K & Ansell Martin P, *Improved timber connections using bonded-in GFRP rods*, Department of Materials Science and Engineering, University of Bath, Bath, UK, 2000.

33 Feng C X & Wang X F, *IIE Trans*, 35 (2003) 11-27.

34 Kopac J, Bahor M & SokoviC M, *Int J Mach Tools Manuf*, 42(6) (2002) 707-716.

35 Phadke M S, *Quality Engineering Using Robust Design* (Prentice-Hall, Englewood Cliffs, NJ), 1989.

36 Ross P J, Taguchi techniques for quality engineering (McGraw-Hill, New York), 1996.