Optimization of Tangential Cutting Force in Turning Operation in Machining of Unidirectional Glass Fiber Reinforced Plastics

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Received: 8 February 2017, Revised: 20 March 2017, Accepted: 12 April 2017

Abstract: In this paper, Taguchi method is applied to find optimum process parameters for turning UD-GFRP rods using polycrystalline diamond cutting tool. The process parameters considered include cutting speed, depth of cut, cutting environment (dry and wet) and feed rate. The experiments were conducted by L_{16} orthogonal array as suggested by Taguchi. Signal to Noise ratio and ANOVA are employed to analyses the effect of turning process parameter on the tangential cutting force. The results from confirmation runs indicated that the determined optimal combination of machining parameters improved the performance of the machining process. The percent contributions of cutting speed (2.46%), depth of cut (73.82%), dry and wet (3.89%) and feed rate (8.02%) in affecting the variation of tangential force are significantly larger (95 % confidence level). It has been found that the wet cutting environment reduces the tangential force. Depth of cut is the factor, which has great influence on tangential force, followed by feed rate.

Keywords: ANOVA, Polycrystalline diamond tool, Taguchi method, Tangential force, Turning process, Unidirectional glass fiber reinforced plastics

Reference: Surinder Kumar, “Optimization of Tangential Cutting Force in Turning Operation in Machining of Unidirectional Glass Fiber Reinforced Plastics”, International Journal of Advanced Design and Manufacturing Technology, Vol. 10/ No. 3, 2017, pp. 21-32.

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1. INTRODUCTION

Conventional machining practices such as turning, milling and drilling are used with composites because of the availability of equipment and experience in conventional machining. Although some of the fibers used in composites are hard, sometimes even harder than the tool material conventional machining is still used. The FRP material removal is accomplished by a series of brittle fractures rather than plastic deformation ahead of the tool Caprino and Nele [1] & Koplev et al. [2]. Wang and Zhang [3], [4] characterized the machining damage in unidirectional FRP subjected to cutting and developed a new mechanics model to predict the cutting forces.

Mahdi and Zhang [5] presented a two-dimensional cutting model to predict the cutting forces in relation to fibre orientations and developed an adaptive three-dimensional finite element algorithm. Kim and Ehmann [6] demonstrated that the knowledge of the cutting forces is one of the most fundamental requirements. This knowledge also gives very important information for cutter design, machine tool design and detection of tool wear and breakage. Santhanakrishnan et al. [7] presented machinability 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 surface roughness. Scanning electron microscope was used for micrograph. 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.

Sreejith et al. [8] observed that the cutting force and the cutting temperature affect the performance of the cutting tools while machining carbon/carbon composites. Lee [9] investigated the machinability of glass fiber reinforced plastics by means of different tool materials and geometries. Three parameters such as cutting speed, feed rate and depth of cut were selected and cutting force measurements were taken using the Kistler (9257B) piezoelectric dynamometer. 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. Rao et al. [10] simulated orthogonal machining of unidirectional carbon fiber-reinforced polymer and glass fiber-reinforced polymer composites using finite element method. The cutting force was the response studied both for experimentally and numerically for a range of fiber orientations, depths of cut, and tool rake angles.

Recent studies on unidirectional glass fiber composites revealed the chip formation mechanism in orthogonal cutting. In case of long oriented glass fiber, degradation of the matrix adjacent to the fiber occurs first, followed by failure of the fiber at its rear side [11]. Isik and Kentli [12] proposed an approach for turning of a glass fiber reinforced plastic composites using cemented carbide tool. Three parameters such as depth of cut, cutting speed and feed rate were selected to minimize the tangential and feed force measurement. Weighting techniques was used. The idea of this technique consists in adding all the objective functions together using different coefficients for each. It means that we change our multi-criteria optimization problem to a scalar optimization problem by creating one function. It was observed that, technique will be more economical to predict the effect of different influential combination of parameters.

Francisco Mata et al. [13] developed a cutting forces prediction model for the machining of carbon reinforced PEEK CF30 using response surface methodology by using Tin-coated cutting tool. Three parameters such as cutting speed, feed rate and depth of cut were selected to minimize the cutting forces. Authors concluded that, the experimental values agreed with the predicted results indicating suitability of the Multiple Regression models. Hussain 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 and the surface roughness was measured by using form talysurf tester. It was found that, the depth of cut shows a minimum effect on surface roughness as compared to other parameters.

Hussain et al. [15] developed cutting power prediction model for turning of glass fiber reinforced plastics composite using response surface methodology. Carbide (K20), Cubic Boron Nitride (CBN) and Polycrystalline Diamond (PCD) tool on turning machine was used and four parameters such as cutting speed, fiber orientation angle, depth of cut and feed rate were selected. Author concluded that, lower power consumption was observed at low cutting speed, low feed, moderate depth of cut and low fiber orientation angle. PCD tool performed better compared to the other two tools used. Ioannis Ntziantzias et al. [16] used Kienzle-Victor model of GFRP work piece. Two parameters such as feed rate and cutting speed were selected to minimize the cutting forces measurements. Cemented carbide (P20) tool was used for turning process. Authors concluded that, the Kienzle-Victor modeling technique can be effectively used for the prediction of cutting forces in machining of GFRP composites. Hussain et al. [17] developed a surface roughness and cutting force prediction model for the machining of GFRP tubes by using carbide tool (K20), cubic boron nitride (CBN) and polycrystalline diamond (PCD) using response surface methodology. 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 forces. It was found that, the polycrystalline diamond (PCD) cutting tool is better than other two tools used.

Surinder Kumar et al. [18] developed a cutting force prediction model for the machining of UD-GFRP using regression modeling by using Polycrystalline diamond cutting tool. Three parameters such as cutting speed, depth of cut and feed rate were selected to minimize the cutting force. It was found that the depth of cut is the factor which has great influence on radial force, followed by feed rate factor than other parameters, whilst feed rate is the least significant parameter. Also, Authors concluded that, the experimental values agreed with the predicted results indicating suitability of the Multiple Regression models. Surinder Kumar et al. [19] investigated the turning process of the unidirectional glass fiber reinforced plastic (UD-GFRP) composites. polycrystalline diamond (PCD) tool on turning machine was used and six parameters such as tool nose radius, tool rake angle, feed rate, cutting speed, depth of cut and along with cutting environment (dry, wet and cooled (5°-7° temperature)) on the surface roughness were produced. It was found that the feed rate is the factor, which has great influence on surface roughness, followed by cutting speed.

Surinder Kumar et al. [20] Investigated the turning process of unidirectional glass fiber reinforced plastics composite using Taguchi's technique and Distance–Based Pareto Genetic Algorithm. PCD cutting tool was used for turning and six parameters such as tool nose radius, tool rake angle, cutting speed; feed rate, cutting environment and depth of cut were selected. It was observed that production rates increase considerably by reducing machining time. Surinder Kumar et al. [21] developed a surface roughness and delamination mathematical prediction model for the machining of unidirectional glass fiber reinforced plastics composite using multiple regression analysis and genetic algorithm by using carbide (K10) cutting tool. It was observed that the single response optimization algorithms based on efficient methodology, genetic algorithm is utilized to optimize machining parameters in the machining of UD-GFRP.

From the ANOVA result, it is concluded that feed rate, cutting speed and depth of cut have significant effect on surface roughness A, B, E and had 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. Meenu and Surinder Kumar [22] used Taugchi's method grey relation analysis to determine the optimal combination of control parameters in turning. The measures of machining performance were cutting forces. It was found that the average of grey relational grade analysis using Taguchi method, depth of cut followed by tool nose radius is found to be the most influential factor for minimization tangential force, feed force and radial force in turning process.

Meenu and Surinder Kumar, [23] developed a surface roughness prediction model for the machining of unidirectional glass fiber reinforced plastics (UD-GFRP) composite using Artificial Neural Network (ANN). PCD cutting tool was used for turning and six parameters such as tool nose radius, tool rake angle, cutting speed, feed rate, cutting environment and depth of cut were selected. The performance of model is found to be good with mean% error -2.0506 and the feasibility of using ANN to predict surface roughness. Regression coefficient is found to be more than 0.9. Meenu Gupta and Surinder Kumar [24] Investigated the turning process of unidirectional glass fiber reinforced plastics composite using Taguchi method and Grey relational analysis.

PCD cutting tool was used for turning and six parameters such as tool nose radius, tool rake angle, cutting speed, feed rate, cutting environment and depth of cut were selected. Performance characteristics such as surface roughness and material removal rate are optimized during rough cutting operation. It was observed that depth of cut is the factor, which has great influence on surface roughness and material removal rate, followed by feed rate. The percentage contribution of depth of cut is 54.399% and feed rate is 5.355%. In this paper Taguchi's DOE approach is used to analyze the effect of turning process parameters; cutting speed, depth of cut, cutting environment (dry and wet) and feed rate, on tangential forces of PCD inserts while machining UD-GFRP and to obtain an optimal setting of these parameters that may result in optimizing tangential forces.

2. MATERIAL AND METHOD

In the present study, Pultrusion process unidirectional glass fiber reinforced composite rods were used. Pultrusion process is an effective method to manufacture composite rod and used to make strong light weight composite materials, in this case fiberglass. 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. It is pulled through using either a hand over hand method or a continuous roller method. This is opposed to an extrusion which would push the material through dies. The diameter of the rod is 42 mm and length is 780 mm. The fiber used in the rod is E-glass and resin used is epoxy. GFRP rods consist of unidirectional fibres that are pulled through a resin bath into the shape of the rod. GFRP is a cheaper option than Carbon or Kevlar, so GFRP rods were used in this work. Its physical and mechanical properties are shown in Table 1.

Table 1 The mechanical and Thermal Properties of the UD-GFRP Material

Sr. No.	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	gm/cc
6	Tensile Strength	6500 or (650)	Kg / cm^2 or (N/mm^2)
7	Compression Strength	6000 or (600)	Kg / cm^2 or (N/mm^2)
8	Shear Strength	255	Kg / cm^2 or (N/mm^2)
9	Modulus of elasticity	3200 or (320)	Kg / cm^2 or (N/mm^2)
10	Thermal Conductivity	0.30	Kcal /Mhc°
11	Weight of Rod 840 mm in length	2.300	Kgs
12	Electrical strength (Radial):	3.5	KV / mm
13	Working Temperature Class:	Class 'F' (155)	Centigrade
14	Martens Heat Distortion Temperature	210	Centigrade
15	Test in oil : (1) At 20° C:, (2) At 100° C:	20 KV/cm 20 KV/cm (50 KV / 25 mm)	KV/cm

3. EXPERIMENTAL WORK

The number of experiments to be conducted to study the effect of machining parameters was arrived using the DOE and the analysis was carried out using the statistical technique, ANOVA. All the turning experiments were conducted in 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 in wet conditions using water - soluble cutting fluid. Sufficient care was taken to remove the highly abrasive UD-GFRP machining chips. A tool holder of ISO coding 58CRV- 4 is used during the turning operation as shown in Fig. 1.

Fig. 1 Tool holder used in the Experiment

The insert used was a polycrystalline diamond insert VBMT 11T302 having grain size of 10 μm (this standard is based on IS 13742 1993). The dynamometer (Dynamic Engineering Equipment), MIRAJ, MIDC and Maharashtra, (INDIA) as shown in Fig. 2 were used for measuring the three component of tool force.

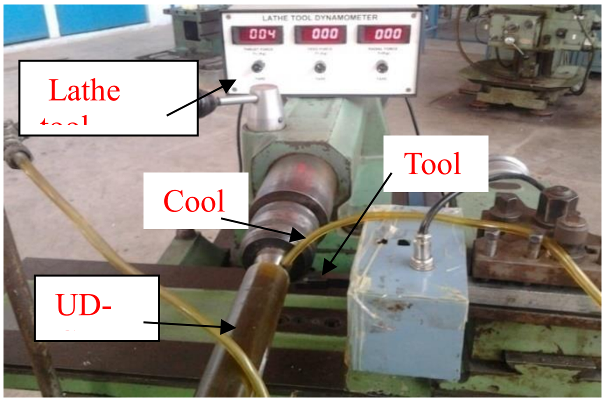

Fig. 2 Set up for Cutting Force Measurement

The machining operations were carried out as per the condition given by the design matrix at random to avoid systematic errors. The forces have been measured several times and averaged. The average tangential force (Ft), which is mostly used in industries, was taken for this study. The tangential forces were measured by using three-point lathe tool dynamometers. From the literature and the previous work done, the independently controllable predominant machining parameters were identified: (1) cutting speed (A), (2) depth of cut (B), (3) cutting environment parameters (dry and wet) (C), and (4) feed rate (D), out of which cutting environment parameters (dry and wet) was specially applied to composite rods. The dry and wet of fibers on the workpiece has been set during the manufacture of rods. The feasible ranges of the above factors were arrived and the factors were set at two different levels. The L_{16} OA (DOF = 15) was thus selected for the present case study. All possible combinations of levels have been included so that there are $2n$ (where n refers to the number of machining parameters *i: e.*, 2^4=16) trials in the experiment. The notations units and their levels chosen are summarized in Table 2.

Table 2 The control parameters and their levels

Process Parameters Design	Process Parameters	Levels	
		Level (1)	Level (1)
A	Cutting Speed / m/min. (rpm)	7.92(60)	25.33(192)
B	Depth of cut /mm	0.2	1.4
C	Cutting environment (Dry and Wet)	1	2
D	Feed rate/ (mm/rev.)	0.1	0.2

Table 3 L_{16} (2^4) Orthogonal array with process parameters and interactions assigned to columns

Sr. No.	1 A	2 B	3 C	4 D	5 AB	6 AC	7 AD	8 BC	9 BD	10 CD	11 ABC	12 ABD	13 ACD	14 BCD	15 ABCD	Average response on, Ft/ kgf
1	1	1	1	1	2	2	2	2	2	2	1	1	1	1	2	16.00
2	2	1	1	1	1	1	1	2	2	2	2	2	2	1	1	6.72
3	1	2	1	1	1	2	2	1	1	2	2	2	1	2	1	30.84
4	2	2	1	1	2	1	1	1	1	2	1	1	2	2	2	34.31
5	1	1	2	1	2	1	2	1	2	1	2	1	2	2	1	9.31
6	2	1	2	1	1	2	1	1	2	1	1	2	1	2	2	2.50
7	1	2	2	1	1	1	2	2	1	1	1	2	2	1	2	27.00
8	2	2	2	1	2	2	1	2	1	1	2	1	1	1	1	23.85
9	1	1	1	2	2	2	1	2	1	1	1	2	2	2	1	13.80
10	2	1	1	2	1	1	2	2	1	1	2	1	1	2	2	5.50
11	1	2	1	2	1	2	1	1	2	1	2	1	2	1	2	59.48
12	2	2	1	2	2	1	2	1	2	1	1	2	1	1	1	53.54
13	1	1	2	2	2	1	1	1	1	2	2	2	1	1	2	11.42
14	2	1	2	2	1	2	2	1	1	2	1	1	2	1	1	3.50
15	1	2	2	2	1	1	1	2	2	2	1	1	1	2	1	46.80
16	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	38.25

The experimental layout and the results are given in table 3. In the table, the first 4 columns indicate the main factors, which are set at different levels, and the remaining columns indicate the interaction effects of factors. For the convenience of recording and processing the experimental data, the upper and lower levels of the parameters are coded as 1 and 2. The tangential forces are the "lower the better" type of quality characteristics. Lower the better S/N ratios are computed for each of the 16 trials and the values are given in Table 4. For the case of minimizing the performance characteristic, S/N ratio is calculated as: Smaller the best characteristics:

$$\text{S/N} = -10 \text{ Log} \frac{1}{n} \sum y^2 \qquad (1)$$

The average of the tangential forces is determined for each trial condition as given in Table 4. In the present study, it has been attempted to achieve the optimal parameter setting for minimizing the tangential forces. In addition, the interactive effects of the factors have also been accounted. The interactions considered between the selected factors are: cutting speed and depth of cut (A×B), cutting speed and cutting environment (dry and wet) (A×C), depth of cut and cutting environment (dry and wet) (B×C), cutting environment (dry and wet) and feed rate (C×D), cutting speed and feed rate (A×D), depth of cut and feed rate (B×D), three-factor interactions ABC, ABD, ACD, BCD, Four-factor interaction ABCD.

Table 4 The experimental results for tangential forces Ft (kgf)

Sr. No.	Ft_1	Ft_2	Ft_3	Average response on, Ft/kgf	S/N ratio (dB)
1	14.00	18.00	16.00	16.00	-24.0824
2	6.75	5.85	7.55	6.72	-16.5474
3	28.16	31.00	33.35	30.84	-29.7823
4	37.23	31.60	34.10	34.31	-30.7084
5	12.23	6.60	9.10	9.31	-19.3790
6	1.40	3.90	2.20	2.50	-7.9588
7	29.00	27.00	25.00	27.00	-28.6273
8	24.25	21.10	26.20	23.85	-27.5498
9	14.10	11.10	16.20	13.80	-22.7976
10	5.20	6.90	4.40	5.50	-14.8073
11	59.10	63.12	56.23	59.48	-35.4874
12	49.23	54.27	57.12	53.54	-34.5736
13	11.25	8.70	14.30	11.42	-21.1533
14	3.20	2.40	4.90	3.50	-10.8814
15	47.10	48.50	44.80	46.80	-33.4049
16	35.30	40.20	39.25	38.25	-31.6526
Total	377.5	380.24	390.7		
	Overall mean of tangential forces = 20.93 kgf				

4.1. ANALYSIS OF MACHINING PARAMETERS

Analysis of the influence of machining parameters on tangential forces has been performed using response table 5, which indicates the response at each level of control factors. The interaction between the variables was also given in the response table. 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 2. For example:

Level 1, $_D$ = Ft1 + Ft 2 + Ft 3 + Ft 4 + Ft 5 + Ft 6 + Ft 7 + Ft 8
=1/8(16.00+6.72+30.84+34.31+9.31+2.50+27.00+23.85) = 18.82
Level 2, $_D$ = Ft 9 + Ft 10 + Ft 11 + Ft 12 + Ft 13 + Ft 14 + Ft 15 + Ft 16
=1/8(13.80+5.50+59.48+53.54+11.42+3.50+46.80+38.25) = 29.04
Difference in level, $_D$ = 10.22 (2)

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 2. Response graph for the machining parameters of the composite machining process is presented in Fig. 3. 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 tangential forces. The optimal conditions are: (1) cutting speed at level 2 (25.33 m/min), (2) depth of cut at level 1 (0.2 mm), (3) wet cutting environment at level 2, (4) feed rate at level 1 (0.1 mm/rev).

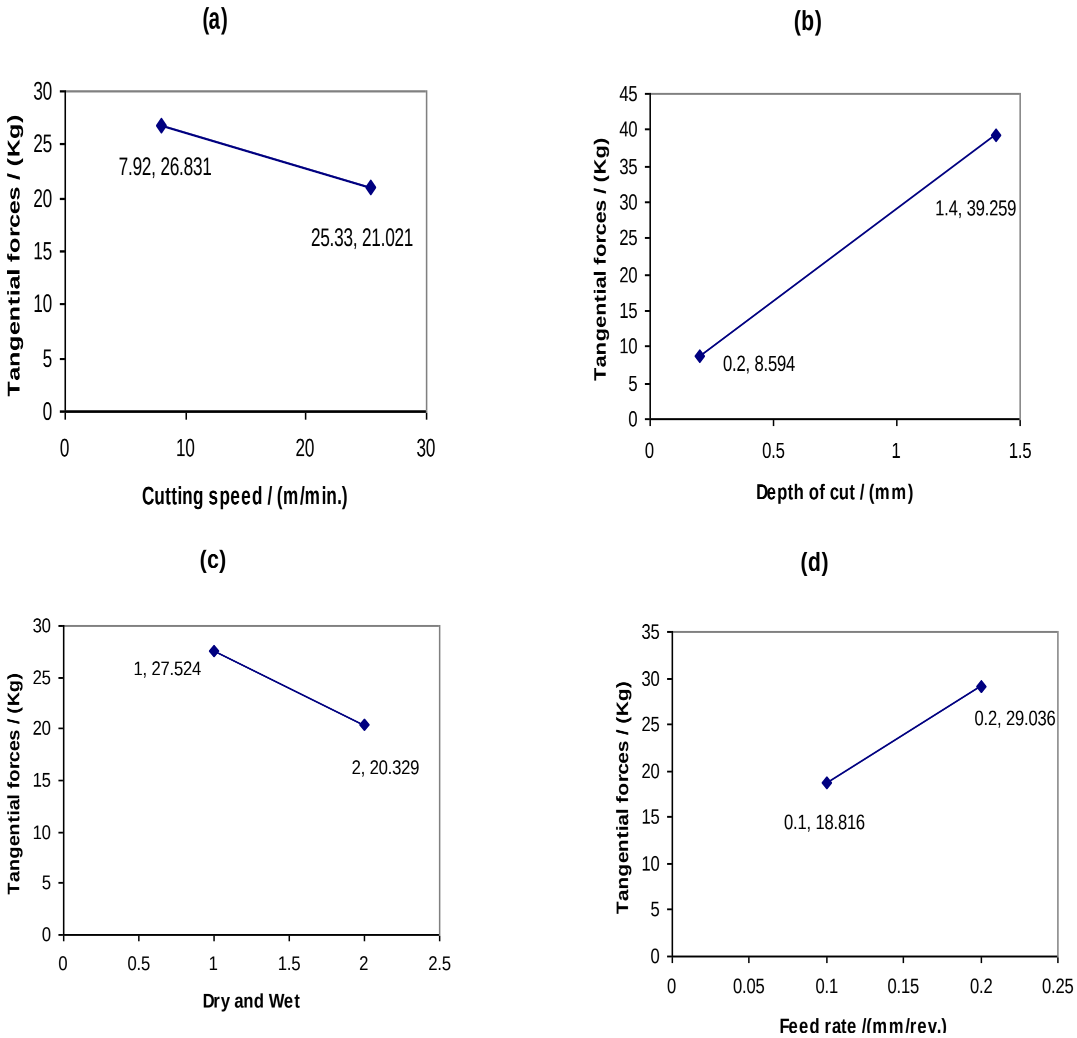

Fig. 3 Response graphs for machining parameters (a) tangential force vs cutting speed, (b) tangential force vs depth of cut, (c) tangential force vs dry and wet and (d) tangential force vs feed rate

Table 5 Response Table for tangential forces

	A	B	C	D	AB	AC	AD	BC	BD	CD	ABC	ABD	ACD	BCD	ABCD
Level 1	26.831	8.594	27.524	18.816	22.793	24.325	24.860	25.613	18.778	24.373	24.681	24.844	24.844	25.189	23.545
Level 2	21.021	39.259	20.329	29.036	25.060	23.528	22.993	22.240	29.075	23.480	23.171	23.009	24.046	22.664	24.308
Differences	-5.810	30.665	-7.195	10.220	2.267	-0.797	-1.867	-3.373	10.297	-0.893	-1.510	-1.835	0.240	-2.525	0.763

Table 6 Response Table for S/N Ratio

	A	B	C	D	AB	AC	AD	BC	BD	CD	ABC	ABD	ACD	BCD	ABCD
Level 1	-26.84	-17.20	-26.10	-23.08	-22.19	-24.90	-24.45	-23.74	-23.29	-23.90	-24.13	-24.54	-24.16	-24.86	-24.36
Level 2	-21.83	-31.47	-22.58	-25.59	-26.49	-23.77	-24.22	-24.93	-25.39	-24.78	-24.54	-24.14	-24.51	-23.81	-24.31
Differeeces	5.00	-14.27	3.52	-2.52	-4.30	1.13	0.23	-1.19	-2.10	-0.88	-0.42	0.40	-0.35	1.05	0.05

4.2. ANALYSIS OF INTERACTION EFFECTS

The interaction between the machining parameters can give very important additional information of the nature and mechanisms about the composite machining process. In engineering problems, normally three- or four-factor interactions have no significant effect (refer response table) and hence, these interactions were not considered. The interaction effects are not being considered in estimating mean and confidence interval around the estimated mean due to poor additivity between parameters and interactions [26]. Table 7 shows the all two-factor interactions considered in this experiment. These are obtained by calculating all four combinations of interaction of two machining parameters. For example, the interaction A×B has four possible combinations of control factor settings: $A_2 \times B_2$, $A_2 \times B_1$, $A_1 \times B_2$, $A_1 \times B_1$. Equation (3) shows how the response values are calculated for interaction A×B at machining parameter settings at $A_2 \times B_2$:

Ft at $A_2 \times B_2 = 1/4(34.31+23.85+53.54+38.25) = 37.49$

By using these interaction values, optimum combinations (minimum effect) are chosen from the table. The interaction between cutting speed and depth of cut (A×B) Fig. 4(a), dry and wet cutting environment and depth of cut (A×C) Fig. 4(b), depth of cut and dry and wet cutting environment (B×C) Fig. 4(c), dry and wet cutting environment and feed rate (C×D) Fig. 4(d), cutting speed and feed rate (A×D) Fig. 4(e), depth of cut and feed rate (B×D) Fig. 4(f), on tangential force is almost a parallel line and the interaction effect is very minimal.

4.3. ANALYSIS OF VARIANCE

Analysis of variance (ANOVA) is a method of portioning variability into identifiable sources of variation and the associated degrees of freedom in an experiment. In statistics, for analyzing the significant effect of the parameters on the quality characteristic, F and P test is used. Table 8(A) shows the results of ANOVA analysis for tangential forces. This analysis was carried out for a level of significance of 5%, *i: e.* for a level of confidence of 95%. From the ANOVA result, it is concluded that A – cutting speed, B – depth of cut, C – dry and wet, D – feed rate, B X D depth of cut X feed rate have significant effect on tangential forces AB, AC, AD, BC, CD and has no effect at 95% confidence level. It is found that depth of cut is more significant factor than other parameters; whilst cutting speed is the least significant parameter. The interaction effects are not being considered in estimating mean and confidence interval around the estimated mean due to poor additivity between parameters and interactions [26].

Table 7 The interaction matrices for insignificant interaction

A×B	C×D	B×D	A×C	B×C	A×D
$A_2 \times B_2$ 37.49	$C_2 \times D_2$ 24.99	$B_2 \times D_2$ 49.52	$A_2 \times C_2$ 17.02	$B_2 \times C_2$ 33.98	$A_2 \times D_2$ 25.19
$A_2 \times B_1$ 4.56	$C_2 \times D_1$ 15.67	$B_2 \times D_1$ 29.00	$A_2 \times C_1$ 25.01	$B_2 \times C_1$ 44.54	$A_2 \times D_1$ 16.85
$A_1 \times B_2$ 41.03	$C_1 \times D_2$ 33.08	$B_1 \times D_2$ 8.56	$A_1 \times C_2$ 23.63	$B_1 \times C_2$ 6.68	$A_1 \times D_2$ 32.88
$A_1 \times B_1$ 12.63	$C_1 \times D_1$ 21.97	$B_1 \times D_1$ 8.63	$A_1 \times C_1$ 30.03	$B_1 \times C_1$ 10.51	$A_1 \times D_1$ 20.79

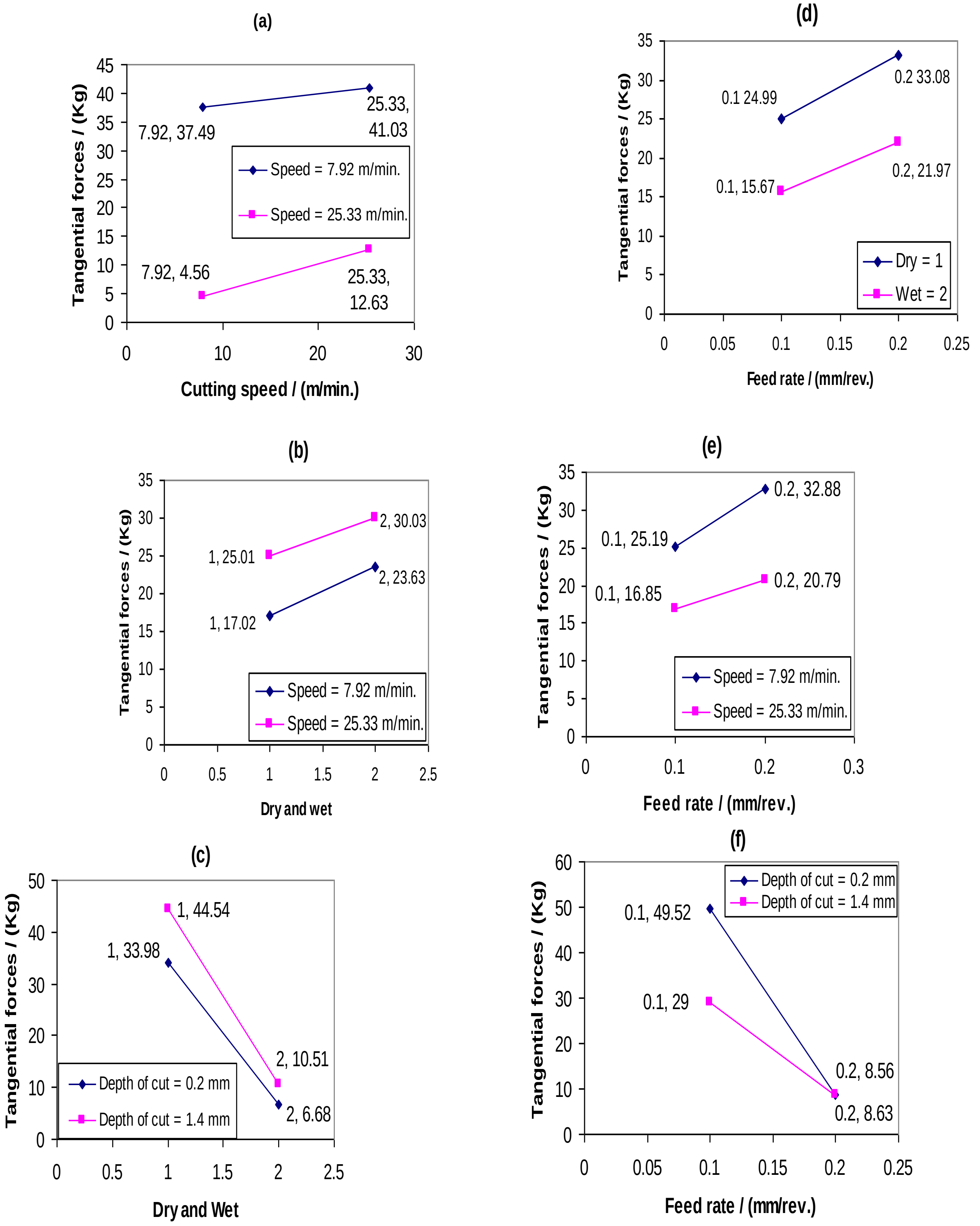

Fig. 4 Interaction graphs (a) cutting speed and depth of cut (A×B), (b) dry and wet cutting environment and depth of cut (A×C), (c) depth of cut and dry and wet cutting environment (B×C), (d) dry and wet cutting environment and feed rate (C×D), (e) cutting speed and feed rate (A×D), (f) depth of cut and feed rate (B×D)

Where $\overline{T_{Ft}}$ = overall mean of tangential force = 20.93 kgf

Hence $\overline{\mu_{Ft}} = (\overline{A_2 - T_{Ft}}) + (\overline{B_1 - T_{Ft}}) + (\overline{C_2 - T_{Ft}}) + (D_1 - \overline{T_{Ft}) + T_{Ft}}$

μ_{Ft} = (21.021−20.93) + (8.594−20.93) + (20.329−20.93) + (18.816−20.93) + 20.93 = 5.788 kgf

Where $F\alpha\ ;(1, fe)$ = F ratio required for α, α = risk, fe = error DOF, Ve = error variance, $n$eff = effective number of replications = $N/$ {1 + [Total DOF associated in the estimate of mean]}, R = number of repetitions for confirmation experiment, N = total number of experiments. Using the values Ve = 10.13 and fe = 5 from (table 8A), N = 16, the confidence interval is calculated. Total DOF associated with the mean (μ_{Ft}) = 3, Total trial = 16, N = 16×3 = 48

$n$eff = 48 / (1 +4) = 9.6, α = 0·05, $F_{0.05;\ 1;\ 5}$ = 6.61 (tabulated).

A confidence interval for the predicted mean on a confirmation run can be calculated using the following equation [26]:

$$CI = \left(F\alpha\ ;(1, fe)\ Ve\ /\ [1/n\text{eff} + 1/R]\right)^{1/2} = \pm\ 5.41\ \text{kgf}$$

The predicted mean of tangential force: $\mu_{Ft} = 5.788$ kgf
The 95% confidence interval of the predicted optimal tangential force is: $[\mu_{Ft} - CI] < \mu_{Ft} < [\mu_{Ft} + CI]$ i.e. [0.378] < 5.788kgf < [11.19].

Table 8 (A) Pooled ANOVA (Raw data: Tangential forces)

Source	SS	DOF	V	F ratio	Prob.	SS/	P (%)
A	135.02	1	135.02	13.33*	0.015	124.89	2.46
B	3761.37	1	3761.37	371.33*	0.000	3751.24	73.82
C	207.07	1	207.07	20.44*	0.006	196.94	3.89
D	417.79	1	417.79	41.24*	0.001	407.66	8.02
A X B	20.57	1	–	Pooled	0.214	–	–
A X C	2.54	1	–	Pooled	0.638	–	–
A X D	13.95	1	–	Pooled	0.293	–	–
B X C	45.50	1	–	Pooled	0.088	–	–
B X D	424.15	1	424.15	41.87*	0.001	414.02	8.15
C X D	3.19	1	–	Pooled	0.599	–	–
T	5081.80	15	10.13			5081.80	100.00
e (pooled)	50.65	5				151.95	2.99

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: $F_{0.05;\ 1;\ 5}$ = 6.61

Table 8(B) S/N Pooled ANOVA (Raw data: Tangential forces)

Source	SS	DOF	V	F ratio	Prob.	SS/	P (%)
A	100.18	1	100.18	80.17*	0.000	98.93	8.98
B	814.81	1	814.81	652.13*	0.000	813.56	73.84
C	49.63	1	49.63	39.72*	0.001	48.38	4.39
D	25.31	1	25.31	20.26*	0.006	24.06	2.18
A X B	73.96	1	73.96	59.19*	0.001	72.71	6.59
A X C	5.07	1	–	Pooled	0.100	–	–
A X D	0.21	1	–	Pooled	0.701	–	–
B X C	5.69	1	–	Pooled	0.086	–	–
B X D	17.60	1	17.60	14.08*	0.013	16.35	1.48
C X D	3.09	1	–	Pooled	0.177	–	–
T	1101.79	15	1.25			1101.79	100.00
e (pooled)	6.25	5				18.75	1.70

5. CONFIRMATION EXPERIMENTS

The confirmation experiment is the final step in verifying the conclusions drawn based on Taguchi's parameter design approach. The optimum conditions are set for the significant factors (the insignificant factors are set at economic levels) and a selected number 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 [26]. The average value of tangential force while turning UD-GFRP with PCD inserts was found to be 2.50 kgf. This result was within the 95% confidence interval of the predicted optimal value of the selected machining characteristic (tangential force). Hence the optimal settings of the process parameters, as predicted in the analysis, can be implemented.

6. CONCLUSIONS

1- Experiments were conducted using a lathe on unidirectional glass fiber reinforced plastics (UD-GFRP) specimens with polycrystalline diamond tool material. The data for tangential force was collected under different cutting conditions for various combinations of cutting speed, depth of cut, feed rate and cutting environment (dry and wet).

2- The contributions of cutting speed (2.46%), depth of cut (73.82%), dry and wet (3.89%) and feed rate (8.02%) in affecting the variation of tangential force are significantly larger than (95% confidence level).

3- Depth of cut is the major factor, which has great influence on tangential force, followed by feed rate.

4- The wet cutting environment reduces the tangential force.

5- From the ANOVA result, it is concluded that BD depth of cut and feed rate have significant effect on tangential force, and AB, AC, AD, BC, CD has no effect at 95% confidence level, where A- cutting speed, B – depth of cut, C – dry and wet, D – feed rate. It is found that depth of cut is more significant factor than other parameters; whilst cutting speed is the least significant parameter.

6- The predicted range of the optimal tangential force: [0.378] < 5.788 kgf < [11.19].

7. REFERENCES

[1] Caprino G., Nele L., “Cutting Forces in Orthogonal Cutting of Unidirectional GFRP Composites Trans”, ASME, Journal Engineering Material Technology, Vol. 118, 1996, pp. 419-425.

[2] Koplev A., Lystrup A., and Vorm T., “The Cutting Process, Chips and Cutting Forces in Machining CFRP”, Composites, Vol. 14, No.4, 1983, pp. 371-376.

[3] Wang X. M., Zhang L. C., “Machining Damage in Unidirectional Fibre-Reinforced Plastics, in: Abrasive Technology: Current Development and Applications I”, World Scientific, Singapore, 1999, pp. 429–436.

[4] Wang X. M., Zhang L. C., “An experimental Investigation into the Orthogonal Cutting of Unidirectional Fibre-reinforced Plastics.”, International Journal Machine Tools Manufacturing, Vol. 43, 2003, pp. 1015–1022.

[5] Mahdi M., Zhang L. C., “An Adaptive Three-Dimensional Finite Element Algorithm for the Orthogonal Cutting of Composite Materials”, Journal Material Processing Technology, Vol. 113, 2001, pp. 368–372.

[6] Kim H. S., Ehmann K. F., “A Cutting Force Model for Face Milling Operations”, International Journal Machine Tools Des Res, Vol. 33, 1993, pp. 651–673.

[7] Santhanakrishnan G., Krishnamurthy R., and Malhotra S. K., “High Speed Steel Tool Wear Studies in Machining of Glass Fibre-Reinforced Plastics”, Wear, Vol.132, 1989, pp. 327-336.

[8] Sreejith P. S., Krishnamurthy R., and Malhotra S. K., “Effect of Specific Cutting Pressure and Temperature During Machining of Carbon/Phenolic Ablative Composite Using PCBN Tools”, Journal of Materials Processing Technology, Vol. 183, 2007, pp. 88–95.

[9] Lee E. S., “Precision Machining of Glass Fibre Reinforced Plastics with Respect to Tool Characteristics”, International Journal Advanced Manufacturing Technology, Vol. 17, 2001, pp. 791–798.

[10] Rao G. V. G., Mahajan P., and Bhatnagar N. “Micro-Mechanical Modeling of Machining of FRP Composites Cutting Force Analysis”, Composite Science Technology, Vol. 67, 2007, pp. 579–593.

[11] Rao G., Mahajan P., and Bhatnagar N. “Machining of UD-GFRP Composites Chip Formation Mechanism”, Composites Science and Technology, Vol. 67, No. 11-12, 2007, pp. 2271-2281.

[12] Isik B., Kentli A., “Multicriteria Optimization of Cutting Parameters in Turning of UD-GFRP Materials Considering Sensitivity”, International Journal Advanced Manufacturing Technology, Vol. 44, 2009, pp. 1144–1153.

[13] Mata F., Beamud E., Hanafi E., Khamlichi A., Jabbouri A., and Bezzazi M., “Multiple Regression Prediction Model for Cutting Forces in Turning Carbon-Reinforced PEEK CF30”, Advances in Materials Science and Engineering, 2010, pp. 1-7.

[14] Hussain S. A., Pandurangadu V., and Palanikumar K., “Surface Roughness Analysis in Machining of GFRP Composite by Carbide Tool (K20)”, European Journal of Scientific Research, Vol. 41, No. 1, 2010, pp. 84-98.

[15] Hussain S. A., Pandurangadu V., and Palanikumar K., “Cutting Power Prediction Model for Turning of GFRP Composites Using Response Surface Methodology”, International Journal of Engineering, Science and Technology, Vol. 3, No. 6, 2011, pp. 161-171.

[16] Ntziantzias I., Kechaglas J., Fountas N., Maropoulos S., and Vaxevanidis N. M., “A Cutting Force Model in Turning of Glass Fiber Reinforced Polymer Composite”, International Conference on Economic Engineering and Manufacturing Systems Brasov, 2011, pp. 24-25.

[17] Hussain S. A., Pandurangadu V., and Palanikumar K., “Machinability of Glass Fiber Reinforced Plastic

(GFRP) Composite Materials", International Journal of Engineering, Science and Technology, Vol. 3, No. 4, 2011, pp. 103-118.

[18] Kumar S., Gupta M., Satsangi P. S., and Sardana H. K., "Multiple Regression Model for Cutting Force in Turning UD-GFRP Using Polycrystalline Diamond Cutting Tool", International Journal of Advanced Engineering Technology, Vol. 3, Issue. 1, 2012, pp. 108-112.

[19] Kumar S., Gupta M., Satsangi P. S., and Sardana H. K., "Optimization of Surface Roughness in Turning Unidirectional Glass Fiber Reinforced Plastics (UD-GFRP) Composites Using Polycrystalline Diamond (PCD) Cutting Tool", Indian Journal of Engineering & materials sciences, Vol.B19, 2012, pp. 163-174.

[20] Kumar S., Gupta M., and Satsangi P. S., "Multiple Performance Optimization in Machining of UD-GFRP Composites by a PCD Tool Using Distance – Based Pareto Genetic Algorithm (DPGA)", Engineering Science and Technology, an International Journal, Vol. 2, Issue. 2, 2013, pp. 49-62.

[21] Kumar S., Gupta M., and Satsangi P. S., "Optimization of Surface Roughness in Turning Unidirectional Glass Fiber Reinforced Plastic (UD-GFRP) Composite Using Carbide (k10) Cutting Tool", Asian academic research journal of multidisciplinary, Vol. 1, Issue. 9, 2013, pp. 105-128.

[22] Gupta M., Kumar S., "Multi-Objective Optimization of Cutting Forces in Turning of UD-GFRP Composite Using Taguchi Grey Relational Analysis", Journal of Mechanical Engineering, Vol. 123, 2013, pp. 166-177

[23] Gupta M., Kumar S., "Prediction of Surface Roughness in Turning of UD-GFRP Using Artificial Neural Network", Mechanica Confab, Vol. 2, Issue. 3, 2013, pp. 46-56.

[24] Gupta M., Kumar S, "Multi-Objective Optimization of Cutting Parameters in Turning Using Grey Relational Analysis", International Journal of Industrial Engineering Computations. Vol. 4, 2013, pp. 547–558

[25] Ravi, S., Balasubramanian, V., Babu, S., and Nemat Nasser, S., "Assessment of Factors Influencing the Fatigue Life of Strength Mis-Matched HSLA Steel Weldments", Mater. Des. 25, 2004, pp. 125–135.

[26] Ross P. J., "Taguchi Techniques for Quality Engineering", McGraw-Hills Book Company, New York, 1988.