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Parametric analysis of GFRP composites in CNC milling machine using Taguchi method

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***Abstract**: Milling composite materials is a difficult task due to its heterogeneity and the number of problems, such as surface delamination, fibre pullout associated with the characteristics of the material and the cutting parameters that appear during the machining process. Glass Fibre Reinforced Plastics (GFRP) composite is considered to be an economic alternative to heavy exotic materials. It is widely used in different fields such as aerospace, oil, automotive and aircraft industries due to their light weight, high modulus, specific strength and high fracture toughness. In this work, a plan of experiment based on Taguchi's L_{27} orthogonal array was established and milling experiments were conducted with prefixed cutting parameters for GFRP composite plates using solid carbide end mills. The machining parameters such as, and fibre orientation angle, helix angle, spindle speed and feed rate are optimized with the objective of minimizing the surface roughness, machining force and delamination factor. The objective was to establish a correlation between cutting parameters and responses. The correlation was obtained by multiple-variable linear regression using Minitab 14 software. Analysis of the influences of the entire individual input machining parameters on the responses has been carried out and significant contribution of parameters is determined by analysis of variance (ANOVA).*
***Keywords** –ANOVA, GFRP composites, L_{27} orthogonal array, milling, Solid carbide end mill.*

I. Introduction

Milling is the common frequently used machining operation in manufacturing parts of fiber-reinforced plastics, because components made of composites are commonly produced by net-shape components that often require the removal of excess material to control tolerances, and milling is used as a corrective operation to produce well-defined and high quality surfaces [1]. Fiberglass composites have become an economic alternative to exotic materials. In recent years, glass fiber-reinforced plastics (GFRP) are being widely used in variety of engineering applications in many different fields such as aerospace, automotive and aircraft industries due to their light weight, high modulus, high specific strength and high fracture toughness [2]. Surface roughness is a characteristic that could affect on dimensional precision, the behavior of the mechanical pieces and production cost. For these reasons there has been a continuous Research and Development with the objective of optimizing cutting parameters to obtain a determined surface roughness [3, 4].

The first theoretical work on FRP was presented by Everstine and Rogers, they have done the theoretical analysis of plane deformation of incompressible compositesreinforced by strong parallel fibers [5]. Mike et al. have developed a surface roughness prediction method using regression analysis for CNC end Milling is the first of its kind in development of the importance of precision machining and surface roughness [6]. Sakuma and Setoand Bhatnagar*et al*. studied the influence of fiber orientation on both the quality of the machined surfaces and tool wear [7, 8]. Takeyama and Lijima studied the surface roughness on machining of GFRP composites. According to them, higher cutting speed causes the rougher and more damaged on the machined surface. This is ascrible to higher cutting temperature, which will result into local softening of work material, also studied the machinability of FRP composites using ultrasonic machining technique [9]. Palanikumar*et al*. attempted to assess the influence of machining parameters on surface roughness in machining GFRP composites. It concludes that the feed rate has more influence on surface roughness followed by cutting speed [10]. Praveen Raj and ElayaPerumalcarried out a study of surface roughness, precision and delamination factor in use of Ti-Namite carbide K10 end mill, Solid carbide K10 end mill and Tipped Carbide K10 end mill on GFRP composite material. They established a correlation between cutting velocity, feed rate and depth of cut with surface roughness and delamination in a GFRP laminates. The investigation reveals that, Ti-Namite coated carbide end mill and tipped carbide end mill produces less damage on GFRP composite material than the solid carbide end mill [11]. The influence of cutting conditions on surface roughness during turning by design of experiments and regression analysis was studied by Paulo Davim [12]. Paulo Davim and Pedro Reis evaluated the cutting parameters (cutting velocity and feed rate) under the surface roughness and damage in milling laminate plates of carbon fibre-reinforced plastics (CFRPs) by Taguchi method [13]. Julie *et al*. presented a study of the Taguchi design application to optimize surface quality in a CNC face milling operation. An orthogonal array and ANOVA were carried out to identify the significant factors affecting surface roughness, and the optimal cutting combination was determined by seeking the best surface roughness (response) and signal-to-noise ratio [14]. Adeel*et al*. presented experimental study to optimize the cutting parameters using two performance measures (workpiece surface temperature and surface roughness). Optimal cutting parameters for each performance measure were obtained employing Taguchi techniques. The results showed that the workpiece surface temperature can be sensed and used effectively as an indicator to control the cutting performance and improves the optimization process, they concluded that it is possible to increase machine utilization and decrease production cost in an automated manufacturing environment [15]. Neseli et al. reported that the tool nose radius is the dominant factor on the surface roughness in turning of AISI steel [16].JagannathMunda et al. investigated the electrochemical micromachining through response surface methodology approach by taking MRR and ROC as separate objective measures, developed mathematical models and analyzed with reference to machining parameters [17].Singh and Bhatnagar made an attempt to correlate the drilling-induced damage with the drilling parameters of unidirectional GFRP composite laminates [18]. Machining force also plays a key role in analyzing the machining process of FRPs. The value of machining force in the work piece is determined using the equation:

$$F_m=\sqrt{(Fx^2 + Fy^2 + Fz^2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Generally, machining force increases with increase in feed rate and decreases with increase in cutting velocity. Evaluation of machining parameters of hand layup GFRP related to machining force was also carried out by Paulo Davim*et al.*on milling using cemented carbide (K10) end mill [19]. A new machinability index was proposed by Paulo Davim and Mata for the turning of hand laid up GFRP materials using polycrystalline diamond (PCD) and cemented carbide (K15) cutting tools. The investigation reveals that the PCD tool performs well compared to cemented carbide (K15) tool in terms of surface roughness and specific cutting pressure [20, 21].

In the present work, a mathematical model has been developed to predict the surface roughness, machining force and delamination of machined GFRP work piece using Taguchi's L_{27} orthogonal array. The "Minitab 14" software is used for regression analysis of the data was collected. The optimum values of the selected variables were obtained by solving the regression equation and by analyzing the response graphs. Analysis of variance (ANOVA) was used for finding the significant parameters. This model can be effectively used to predict the surface roughness, machining force and delamination of the machined GFRP components.

II. Methodology and measurements

2.1 Taguchi method

Taguchi methods [22] have been widely utilized in engineering analysis and consist of a plan of experiments with the objective of acquiring data in a controlled way, in order to obtain information about the behavior of a given process. The greatest advantage of this method is the saving of effort in conducting experiments; saving experimental time, reducing the cost, and discovering significant factors quickly. Taguchi's robust design method is a powerful tool for the design of a high-quality system. In addition to the S/N ratio, a statistical analysis of variance (ANOVA) can be employed to indicate the impact of process parameters on surface roughness, machining force and delamination factor.

The steps applied for Taguchi optimization in this study are as follows.

- Select noise and control factors
- Select Taguchi orthogonal array
- Conduct Experiments
- Measurement of surface roughness, machining force and delamination factor
- Analyze results; (Signal-to-noise ratio)
- Predicting optimum levels for each response

2.2 Experimental Details

Glass fibre reinforced plastics (GFRP) composite plates made by Hand lay-up method are used for these experiments. GFRP plates are of 100 mm x 60 mm x 5 mm thick with 12 lay-up with desired fibre orientation (15°, 60° and 105°) are used for the milling operations. The cutting tool is made up of solid carbide end mill of 5 mm diameter. The solid carbide end mill of different helix angles (25°, 35°, and 45°) are shown in Fig.1.

Figure 1. Solid carbide end mill with different helix angles

The fibre orientations are defined in clockwise with reference to the cutting direction as shown in Fig.2. The experiments are conducted based on Taguchi L_{27} orthogonal array using a CNC milling machine. The CNC milling machine is an automated machinery, and its specifications are given in Table 1. The fixation of the composite material in the machining centre is as shown in Fig.3 to make sure that vibrations and displacement are eliminated.

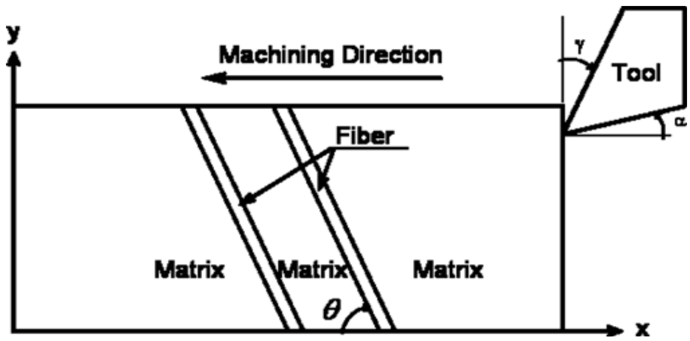

Figure 2. Notation of the fibre orientation with respect to cutting tool movement.

Figure 3. Fixation of GFRP composite plate by using clamps in the machining centre

2.3 Measurements

The surface roughness value of the machined surfaces is measured in order to analyze the surface finish quality. The surface roughness of a machined product could affect contact causing surface friction, wearing, light reflection, heat transmission, the ability for distributing and holding a lubricant, coating, and resisting fatigue. The surface roughness (Ra) was evaluated using stylus type profilometerMitutoyo SJ-201. For each test, five measurements were made over milling surfaces, according to Fig.4. Considering the number of measurements to be carried out, a programmable technique was used, by previously selecting a roughness profile, the cut-off (0.8 mm) and the roughness evaluator parameter (Ra) according to ISO.

Table 1. Specification of the CNC milling machine

Type of machine	Vertical machine centre
Make	Hartford, Taiwan
Table size	810 x 400 mm
Spindle motor power	8 KW
Spindle speed	60-9000 rpm
Feed	1-7000 mm/min
X axis	510 mm
Y axis	400 mm
Z axis	400 mm
Accuracy (Positioning)	± 0.005/300 mm

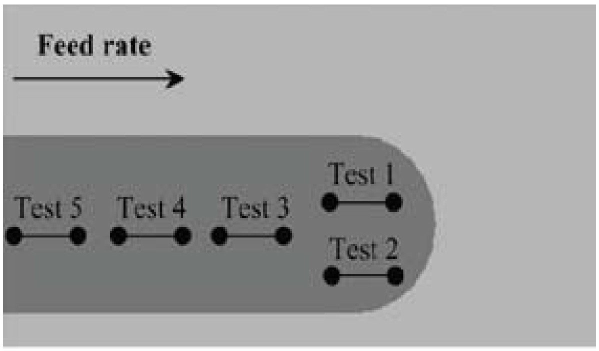

Figure 4. Diagram of measurement that were made over each milling surface

The damage caused on the GFRP composite material was measured perpendicular to the feed rate with a tool maker's microscope, as observed in Fig.5. The composite material was positioned and fixed on the XY stage glass of the microscope, and then the alignment of an initial measuring point with one of the cross-hairs was made on the machined feature. Moving the XY stage glass by turning the micrometer head with a Digital Counter to the final point with the same cross-hair has been measured the damage (maximum width). After the measurement of the maximum width of damage (W_{max}) suffered by the material, the damage normally assigned by delamination factor (Fd) was determined. This factor is defined as the quotient between the maximum width of damage (W_{max}), and the width of cut (W). The value of delamination factor (Fd) can be obtained by the following equation:

$$Fd = \frac{Wmax}{W} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

W_{max} being the maximum width of damage in mm and W be the width of cut in mm.

The force measurement was carried out using a Kistler dynamometer. The data acquisition was carried out by appropriate software called Dynawarekistler. The value of machining force in the work piece is determined using the equation (1).

2.4Plan of experiments

The experiments are planned using Taguchi's orthogonal array in the design of experiments (DOE), which helps in reducing the number of experiments. The experiments were conducted according to orthogonal array. The four cutting parameters selected for the present investigation is Fibre orientation angle (ϴ) in degrees, Helix angle (Φ) in degrees, Spindle speed (N) in rpm, Feed rate (f) in mm/rev. Taguchi's orthogonal array of L_{27} is considered for this work. This needs 27 runs and has 26 degrees of freedom. The machining parameter used and their levels are shown in Table 2. The experimental test conditions and observed data based on L_{27} orthogonal array are shown in Table 3.

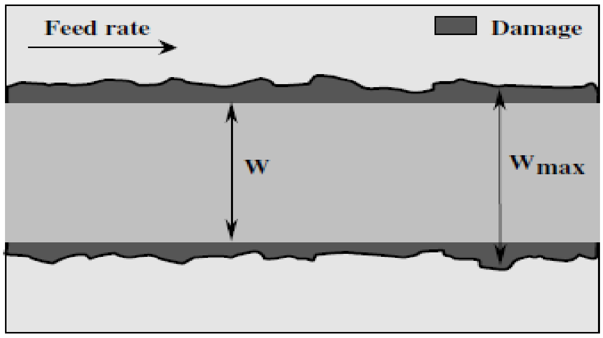

Figure 5. Diagram of the measurement of the width of maximum damage

Table 2. Process control parameters and their levels

			Levels		
Process parameters	Units	Notation	1	2	3
Fibre orientation angle	o(degrees)	Θ	15	60	105
Helix angle	o(degrees)	Φ	25	35	45
Spindle speed	rpm	N	2000	4000	6000
Feed rate	mm/rev	f	0.04	0.08	0.12

Table 3, Experimental test conditions and observed data

Test No.	Fibre orientation angle (degrees)	Helix angle (degrees)	Spindle speed (rpm)	Feed rate (mm/rev)	Surface roughness, Ra (μm)	Machining force, Fm (N)	Delamin-ation factor, Fd
1	15	25	2000	0.04	0.91	15.27	1.009
2	15	25	4000	0.08	0.85	20.78	1.015
3	15	25	6000	0.12	0.95	22.79	1.019
4	15	35	2000	0.08	1.10	19.25	1.025
5	15	35	4000	0.12	1.18	21.64	1.012
6	15	35	6000	0.04	0.92	14.21	1.021
7	15	45	2000	0.12	1.59	20.79	1.032
8	15	45	4000	0.04	1.32	13.54	1.024
9	15	45	6000	0.08	1.30	18.15	1.017
10	60	25	2000	0.04	1.08	26.24	1.011
11	60	25	4000	0.08	1.25	28.16	1.021
12	60	25	6000	0.12	1.29	30.14	1.034
13	60	35	2000	0.08	1.62	24.32	1.040
14	60	35	4000	0.12	1.69	31.84	1.057
15	60	35	6000	0.04	1.48	21.19	1.031
16	60	45	2000	0.12	1.82	32.15	1.067
17	60	45	4000	0.04	1.58	20.79	1.058
18	60	45	6000	0.08	1.62	25.62	1.061
19	105	25	2000	0.04	1.39	39.24	1.038
20	105	25	4000	0.08	1.64	37.25	1.047
21	105	25	6000	0.12	1.72	59.61	1.075
22	105	35	2000	0.08	1.98	39.25	1.059
23	105	35	4000	0.12	2.08	41.52	1.079
24	105	35	6000	0.04	1.68	29.72	1.032
25	105	45	2000	0.12	2.48	38.62	1.092
26	105	45	4000	0.04	2.06	29.15	1.047
27	105	45	6000	0.08	2.12	19.26	1.057

III. Results and discussions

The results of the milling tests allowed the evaluation of the GFRP composite material manufacture by hand-lay up, using solid carbide end mills. The Machinability was evaluated by surface roughness (Ra), machining force (Fm) and delamination factor (Fd).

3.1 Influence of the cutting parameters based on S/N Ratio

Table 3 shows the results of the surface roughness (Ra), machining force (Fm) and delamination factor (Fd) as a function of the cutting parameters for the GFRP composites. Table 4-6 illustrates the results of Taguchi analysis (S/N ratio) for surface roughness, machining force (Fm) and delamination factor (Fd) using the approach of smaller is better.

From Table 3 it is observed that the fibre orientation angle is the most significant parameter followed by he lix angle, feed rate and spindle speed for the surface roughness of GFRP composites. From Table 4 it is understood that the fibre orientation is the most significant parameter followed by feed rate, helix angle and spindle speed for machining force of GFRP composites. From Table 5 also the fibre orientation is the most significant parameter followed by feed rate, helix angle and spindle speed for delamination factor of GFRP composites. This shows that, the influence of machining parameters on machining force and delamination factor are same. From the above analysis, the fibre orientations are seen to make the largest contribution to the overall performance.

Table 4.Signal to noise ratios for the surface roughness of GFRP composites

Levels	Factors			
	ϴ	Φ	N	f
1	-0.8426	-1.5567	-3.4199	-2.5065
2	-3.3707	-3.3884	-3.3158	-3.1968
3	-5.4846	-4.7529	-2.9622	-3.9947
Delta	4.6420	3.1963	0.4577	1.4881
Rank	1	2	4	3

Table 5. Signal to noise ratio for the machining force of GFRP composites

Levels	Factors			
	ϴ	Φ	N	f
1	-25.20	-29.22	-28.61	-26.81
2	-28.44	-28.16	-28.24	-27.90
3	-31.03	-27.28	-27.81	-29.96
Delta	5.83	1.93	0.79	3.15
Rank	1	3	4	2

Table 6.Signal to noise ratio for the delamination factor of GFRP composites

Levels	Factors			
	ϴ	Φ	N	f
1	-0.1661	-0.2542	-0.3501	-0.2567
2	-0.3578	-0.3353	-0.3388	-0.3227
3	-0.4920	-0.4265	-0.3271	-0.4365
Delta	0.3258	0.1723	0.0231	0.1798
Rank	1	3	4	2

3.2 Effect of process parameters on surface roughness, machining force and delamination factor based on response table

The influence of different machining parameters on milling of GFRP composites can be studied by using response graphs and response tables. The influence of cutting parameters on surface roughness, machining force and delamination factor are shown in Fig. 6-8 and their main effects are shown in Table 7-9. From the figure 6, it is realized that surface roughness increases with increasing the fibre orientation angle, helix angle and feed rate, whereas the surface roughness decreases with increasing the spindle speed. Based on the main effect plot and response table for surface roughness, the optimal level of each parameter is set at ϴ1 Φ1 N3 f1 for the surface roughness.

From the figure 7, it is observed that machining force value increases with increasing the fibre orientation angle and feed rate, whereas the delamination factor value decreases with increasing of the helix

angle and spindle speed. Based on the main effect plot and response table for machining force, the optimal level of each parameter is set atϴ1 Φ3 N3 f1 for machining force.
From the figure 8, it is observed that delamination factor value increases with increasing the fibre orientation angle, helix angle and feed rate, whereas the delamination factor value decreases with increasing of the spindle speed. Based on the main effect plot and response table for delamination factor, the optimal level of each parameter is set atϴ1 Φ1 N3 f1 for delamination.

Table 7. Response table for surface roughness

Levels	Factors			
	ϴ	Φ	N	f
1	1.124	1.231	1.552	1.380
2	1.492	1.526	1.517	1.498
3	1.906	1.766	1.453	1.644
Optimum levels	ϴ1	Φ1	N3	f1

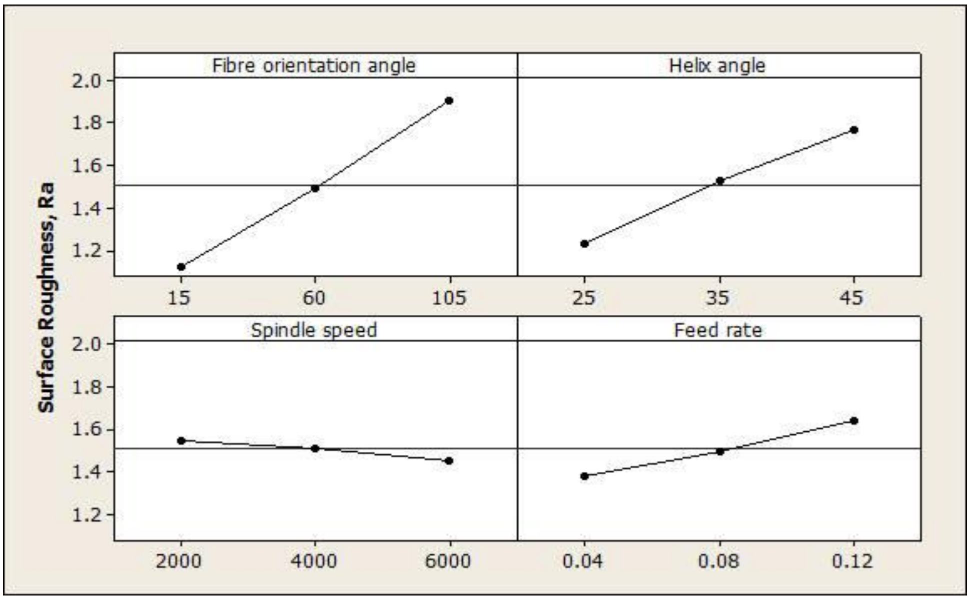

Figure 6. Illustration of factor effects on surface roughness

Table 8. Response table for machining force

Levels	Factors			
	ϴ	Φ	N	f
1	18.49	31.05	28.35	23.26
2	26.72	26.99	27.19	25.78
3	37.07	24.23	26.74	33.23
Optimum level	ϴ1	Φ3	N3	f1

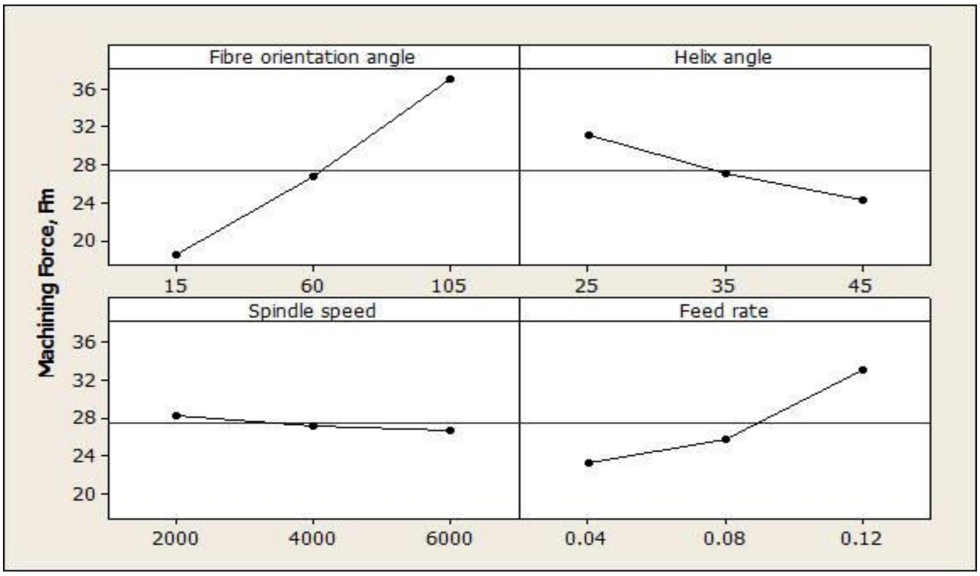

Figure 7. Illustration of factor effects on machining force

Table 9. Response table for delamination factor

Levels	Factors			
	ϴ	Φ	N	f
1	1.019	1.030	1.041	1.030
2	1.042	1.040	1.040	1.038
3	1.058	1.051	1.039	1.052
Optimal level	ϴ1	Φ1	N3	f1

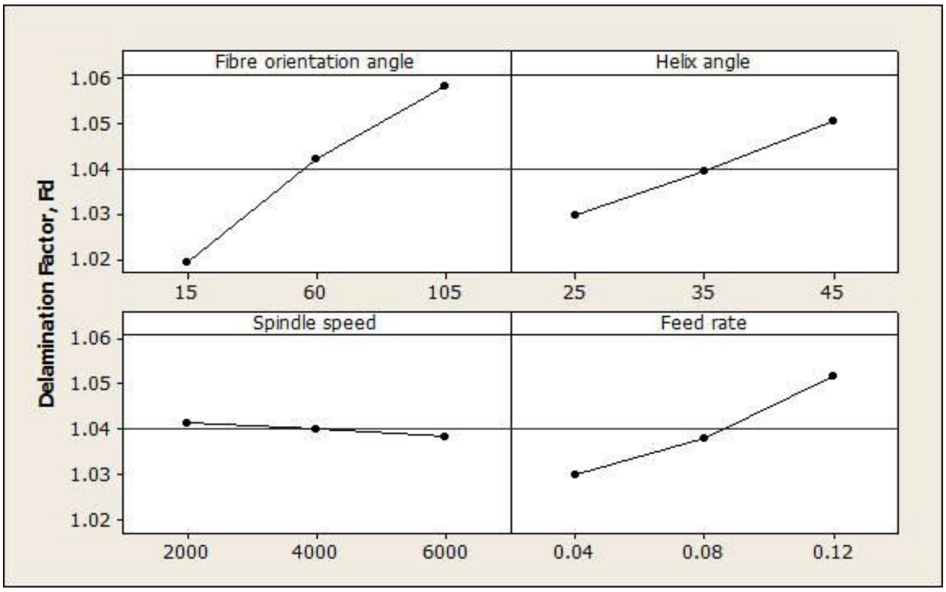

Figure 8. Illustration of factor effects on delamination factor

3.3 ANOVA for GFRP composites

ANOVA is carried out from the data of Table 3 and is shown in Table 10-12. From Table 10, it is found that the factor fibre orientation angle has statistical and physical significance (P = 60.48%), on the surface roughness of GFRP composite materials. The error associated to the table ANOVA for surface roughness was approximately 3.21%.

From Table 11, it is observed that the factor fibre orientation angle has statistical and physical significance (P = 56.34%), on the machining force of GFRP composite materials. The error associated to the table ANOVA for machining force was approximately 18.08%

From Table 12, it is observed that the factor fibre orientation angle has statistical and physical significance (*P* = 51.05%), on the delamination factor of GFRP composite materials. The error associated to the table ANOVA for delamination factor was approximately 18.46%

From the ANOVA tables the factor fibre orientation angle has more percentage contribution and spindle speed has less percentage contribution on surface roughness, machining force and delamination factor for GFRP composite materials.

Table 10. ANOVA for surface roughness

Factors	Sum of square	Degree of freedom	Mean square	F test	Percentage contribution	Rank
Θ	2.74872	2	1.37436	169.31	60.48	1
Φ	1.28979	2	0.64489	79.45	28.37	2
N	0.04516	2	0.02258	2.78	00.99	4
f	0.31594	2	0.15797	19.46	06.95	3
Error	0.14611	18	0.00812		03.21	
Total	4.54572	26			100	

Table 11. ANOVA for machining force

Factors	Sum of square	Degree of freedom	Mean square	F test	Percentage contribution	Rank
Θ	1559.89	2	779.94	28.05	56.34	1
Φ	212.03	2	106.02	3.81	07.66	3
N	12.36	2	6.18	0.22	00.44	4
f	483.96	2	241.98	8.70	17.48	2
Error	500.58	18	27.81		18.08	
Total	2768.83	26			100	

Table 12. ANOVA for delamination factor

Factors	Sum of square	Degree of freedom	Mean square	F test	Percentage contribution	Rank
Θ	0.0069502	2	0.0034751	24.89	51.05	1
Φ	0.0019247	2	0.0009623	6.89	14.14	3
N	0.0000376	2	0.0000188	0.13	00.28	4
f	0.0021882	2	0.0010941	7.84	16.07	2
Error	0.0025133	18	0.0001396		18.46	
Total	0.0136140	26			100	

3.4 Regression analysis

The correlation between cutting parameters (fibre orientation angle, helix angle, spindle speed and feed rate) and responses (surface roughness, machining force and delamination factor), for GFRP composite material are obtained by regression analysis with a sample size (n) of 27. The regression equation for surface roughness, machining force and delamination factor are obtained as follows:

$Ra = - 0.114 + 0.00868\ \Theta + 0.0267\ \Phi - 0.000025\ N + 3.31\ f\ (R^2 = 96.79\%)$ ……… (3)

$Fm = 18.6 + 0.206\ \Theta - 0.341\ \Phi - 0.000401\ N + 125\ f\ (R^2 = 81.92\%)$………………. (4)

$Fd = 0.959 + 0.000435\ \Theta + 0.00103\ \Phi - 0.000001\ N + 0.272\ f\ (R^2 = 81.54\%)$……… (5)

Θ being fibre orientation angle in degrees, Φ being helix angle in degrees, N being spindle speed in rpm and f being feed rate in mm/rev.

These equations can be used to evaluate the milling induced surface roughness, machining force and delamination factors by varying the machining parameters.

IV. Conclusion

From the experimental results, the following conclusions are find out from milling GFRP composite materials with solid carbide end mill using Taguchi's L_{27} orthogonal array:

1. Fibre orientation angle is the most significant parameter and spindle speed is the least significant parameter for milling of GFRP composite with the objective of minimizing surface roughness, machining force and delamination factor.
2. The optimal level of parameters for minimizing surface roughness, machining force and delamination factor are Θ1Φ1N3f1, Θ1 Φ3 N3 f1 and Θ1 Φ1 N3 f1 respectively.

3. The surface roughness and delamination factor increases with increase of fibre orientation angle, helix angle and feed rate, and decreases with increasing the spindle speed.
4. The machining force increases with increase of fibre orientation angle and feed rate, and it decreases with increasing the helix angle and spindle speed.
5. Fibre orientation angle is the cutting parameter that presents the highest statistical and physical influence on surface roughness (60.48 %), on machining force (56.34 %) and on delamination factor (51.05 %).
6. The equations (3)-(5) can be effectively used to predict the milling induced surface roughness, machining force and delamination factors for GFRP composites.

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