Machinability Characterization in Milling of GFRP Composites by Taguchi's Technique

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ABSTRACT

The machining of composite materials are often used in aerospace, automobile and other industrial applications to produce machined slots, holes and grooves, where metal inserts are inevitable in case of joining or affixing with mating parts. The damages initiated due to machining process are generally lead to stress concentration. And further promotes process of damage by crack initiation and growth may lead to catastrophic failure of entire structure while in service. It is necessary to minimizing the damages in machining of GFRP composites for rejection of products and to maintain better tolerance between mating parts. Hence the present investigation aims to illustrate the machinability of GFRP composites with respect to desirable optimum process parameters. The experiments were conducted with specially designed brazed carbide tipped end mill tool in accordance to Design of Experiments (DOE). Taguchi analysis combined with Analysis of Variance (ANOVA) and was carried out to identify the effects of machining quality parameters (speed 'N', feed rate 'f', depth of cut 'd', fiber orientation angle 'Ѳ', and fiber volume fraction 'ϕ_i') on machinability outputs (surface roughness, machining force and delamination factor). The correlation was also obtained by Multiple Regression Analysis (MRA) to establish parametric relationship between the experimental process parameters and output responses. The calculated values of MRA have been found very close to experimental values for almost all cases. Finally, the results of data were also illustrated and analyzed with Scanning Electron Microscope (SEM).

KEY WORDS: Compression moulding technique, milling tool dynamometer, specially designed brazed carbide tipped end mill tool, SEM, Taguchi's Method.

1. INTRODUCTION

Fiber Reinforced Polymer (FRP) composites are characterized by their greatness when compared with metals, better in high strength to weight ratio, high stiffness, ease of manufacturing and better in corrosion resistance. Hence GFRP composites frequently used in aerospace, automobile and other commercial applications. Smith (1990), pointed that the ability of secondary machining (turning, drilling and milling) of FRP materials depend on many aspects such as physical properties, fiber types, fiber orientations, variability of matrix material and fiber volume fraction. It is necessary of secondary machining processed FRP materials to obtaining the closer dimensional accuracy in a specified manner, for minimization of damages in terms of reduce the wastage of time, cost and improvisation of production quality. Considerable amount of literature is readily available in the machinability of Glass Fiber Reinforced Polymer (GFRP) composites, with limited selection of work on milling control process parameters. Therefore, optimization of machining process parameters for all kind of FRP composites is seemed to be an emerging area in research. Due to anisotropic nature, non-homogeneity, abrasive nature of fibers, poor surface quality is regularly seen where GFRP composites are machined. Also delamination, sub-surface damages and fiber pullout will takes place after machining. There are many research studies were exposed for improving the machinability of FRP materials from last five decades. Palanikumar (2008; 2010), reported that the results of machinability studies such as evaluation in delamination damage and delamination mechanisms in drilling of FRP composites. Naveen Sait (2009), used Taguchi's technique to optimize the machining process parameters in drilling of GFRP composite pipes. Yet, a limited studies in milling of FRP composites has offered to characterize the surface quality and cutting force induced failures. Sheikh Ahmad (2007), developed a mechanistic force prediction model in milling of unidirectional (UD) carbon fiber-reinforced polymer (CFRP) composites, and analyze the constructive relationship between machining process parameters and machinability output, namely, surface roughness, machining force and delamination factor. Davim (2004), have studied a wide range of machining parameters are processed by Analysis of Variance (ANOVA). Bhatnagar (2007), submitted a machining induced damage study in milling of Carbon Fiber Reinforced Plastics (CFRP) and determine the machinability characteristics found that the spindle speed plays a key role on surface roughness and delamination. However, a limited number of researchers have reported the experimental results on simple aspects of FRP's milling machinability characteristics, such as machining forces and delamination factor. Apart from Azmi (2012, 2013), have presented valuable results for improving the surface quality with improved tool life and evaluating the machining forces in milling of GFRP composites. And SEM images were used to illustrate the surface integrity and morphology of milled laminates. But their studies were limited only three machining parameters, namely, cutting speed, feed rate and depth of cut. In this connection, extending the above investigational studies for minimize the machined surface defects and thereby reducing the machining forces, surface roughness and delamination factor at optimum process parametric levels. Consequently, conduction of experimentation and analyze the data by using Taguchi design method and ANOVA model. Here five input quality factors selected as machining process parameters (Spindle speeds are 960RPM, 1153RPM and 1950 RPM, feed rates are 1 mm/Sec, 2 mm/Sec and 3 mm/Sec, depth of cuts are 1mm, 2mm and 3mm, fiber orientation angles 0^0, $45^0$and 90^0, and fiber volume fractions are 40%, 50% and 60% respectively. The adequacy of the developed models has confirmed through the coefficient of determination (R^2) and these tests confirmed under randomly selected conditions.

2. EXPERIMENTAL SETUP AND PROCEDURE

Schematic of machining: The work piece material selected for the investigation is E-glass uni-directional (fiber orientations of 0^0,45^0, and 90^0)$_{12}$ glass fiber reinforced polymer composites fabricated by hand lay-up compression moulding technique. Find the fiber volume fraction (V_f) of composites according to (ASTM D2548-68) and obtained 'V_f 'as 40%, 50%and 60%. GFRP laminates are shaped by size of 100mm x 100mm x 10 mm by diamond dressed abrasive wheel cutter. In this study, all of the machining operations are carried out on a conventional universal milling machine incorporated by high speed spindle motor 10HP to perform slots on work pieces (figure.1) with specially designed carbide tipped end mill of 10mm diameter (figure.2). The machining component forces are (F_X-Feed force, Fy-Cutting force and F_z-Thrust force, and consider the resultant force 'F' as the machining force and is obtained by $F = \sqrt{F_x^2+ F_y^2+ F_z^2}$). Measuring all forces by using mill tool dynamometer with range of force measurement in all co-ordinate directions as 0 to 50 Kgf. The surface roughness was measured along the direction of fiber ply of machined slot with Mitutoyo profilometer as shown in figure.1(b), where the cut-off value and transfer length were set as 0.5mm/sec 5m. The centreline average (R_a) method is used and takes the surface roughness values at three different places along the machined slot. In addition, the cutting speed (RPM), feed rate (mm/Sec), depth of cut (mm), fiber orientations (Degrees), and fiber volume fraction (%) are the controlled input process parameters in this investigation. Moreover, the damages of machined slot widths were measured at three different places by using a travelling microscope. Hence, the damage factor (F_d) is calculated by taking the average value. Therefore, F_D= W $_{max}$/W. Where the W_{max} is the maximum machined slot width and 'W' is a tool diameter in millimeters.

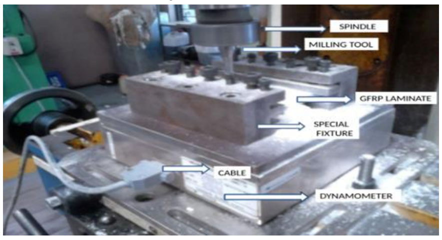

Figure.1(a). Machining of GFRP laminate plate is properly fixed in machining center by special designed fixture

(b) Measurement of surface roughness by Mitutoyo Talysurf

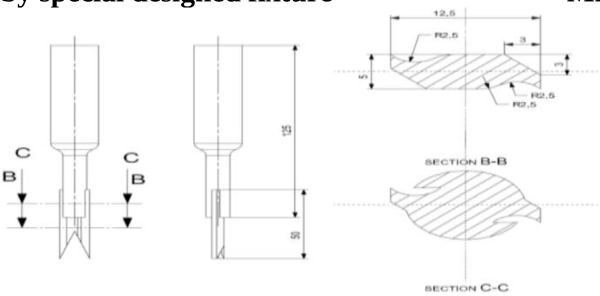

Figure. 2. Details of specially designed carbide tipped end mill tool

Finally, the experimental work excellence was illustrated with a scanning electron microscope (SEM) images.

Tool specifications

Tool clearance angle - 10^0-12^0

Tool Rake angle - 35^0

Tool clearance angle - 14^0

Taguchi's Experimental design and selection of process parameters: Extensive and expensive experimentations would be needed to evaluate the machinability of composites. Hence, experimental approach of machinability assessments will be obtained through statistically designed tests, commonly known as design of experiment (DOE). DOE methodology involves full factorial as well as partial or fractional approaches. In this study, Taguchi DOE method was used to design the experimental matrix as per Kaneeda (1989), and arrange the experiments according to orthogonal array (OA) which can significantly reduce the number of experiments. In the present work different combinations of machining parameters namely speed 'N', feed rate 'f', depth of cut 'd', fiber orientation angle 'ϴ', and fiber volume fraction 'ϕ_i' that effects on the surface roughness (R_a), machining force (F) and delamination factor (F_d). In Taguchi method, the average value of experimental response and its corresponding signal to noise ratio (S/N) of each run can be calculated to analyze the effects of the machining parameters. S/N ratio represents both the average (mean) and variation (standard deviation) of the experimental results. Here aim is to minimize the surface roughness, machining force and delamination factor. Hence, the experimental response the S/N ratio can taking as 'the lower the better'. The controlling process parameters for conducting the experimentation as shown in the table 1 and experimental run as per the Taguchi DOE as revealed in table2.

Table. 1. Control Process parameters and their levels

			Levels		
Process Parameters	**Units**	**Notation**	**1**	**2**	**3**
Spindle speed	RPM	N	960	1153	1950
Feed rate	Mm/sec	f	1	2	3
Depth of cut	'mm'	D	1	2	3
Fiber orientation	Degrees	ϴ	0	45	90
Fiber volume fraction	Percentage	ϕ_i	40	50	60

Table.2. Experimental test conditions and observation data

Exp. No.	Spindle speed (N) in RPM	Feed rate (f) in mm/Sec	Depth of cut (d) in 'mm'	Fiber orientation angel (ϴ)in 'Degrees'	Fiber volume fraction (ϕ_i) (%)	Surface roughness (R_a) 'µm'	Machining force (F) in Newton	Delamination factor (F_d)
1	960	1	1	0	40	1.752	16.580	1.102
2	960	1	1	0	50	1.730	17.263	1.093
3	960	1	1	0	60	2.268	18.231	1.155
4	960	2	2	45	40	1.923	19.250	1.158
5	960	2	2	45	50	1.985	17.036	1.110
6	960	2	2	45	60	2.128	17.036	1.163
7	960	3	3	90	40	1.895	18.755	1.140
8	960	3	3	90	50	2.213	19.960	1.232
9	960	3	3	90	60	2.266	20.470	1.236
10	1153	1	2	90	40	2.033	18.122	1.125
11	1153	1	2	90	50	2.216	21.145	1.234
12	1153	1	2	90	60	2.302	21.465	1.286
13	1153	2	3	0	40	1.562	17.584	1.143
14	1153	2	3	0	50	1.963	19.896	1.206
15	1153	2	3	0	60	1.998	18.968	1.195
16	1153	3	1	45	40	1.035	16.947	1.096
17	1153	3	1	45	50	1.896	19.215	1.238
18	1153	3	1	45	60	1.849	21.136	1.204
19	1960	1	3	45	40	1.803	20.135	1.214
20	1960	1	3	45	50	1.789	21.035	1.224
21	1960	1	3	45	60	1.953	21.259	1.230
22	1960	2	1	90	40	2.102	19.964	1.238
23	1960	2	1	90	50	2.034	20.135	1.196
24	1960	2	1	90	60	2.216	22.031	1.224
25	1960	3	2	0	40	1.689	17.657	1.095
26	1960	3	2	0	50	1.798	17.268	1.194
27	1960	3	2	0	60	1.768	18.842	1.203

3. RESULTS AND DISCUSSION

Influence of the cutting process parameters on the surface roughness based on S/N Ratio: Table.2, shows the results of the surface roughness (Ra), machining force (F) and delamination factor (Fd) as a function of the input cutting process parameters for various GFRP composites. Tables.3-5 accomplish the results of Taguchi analysis (S/N ratio) for surface roughness, machining force (F) and delamination factor (Fd) using the approach of smaller is the better. From the table.3, it is detected that the fiber volume fraction and fiber orientation angle is most influenced parameter fallowed by feed rate, spindle speed and depth of cut for the influenced surface roughness. From the table.4, it is observed that the fiber orientation angle is most exceptional parameter followed by fiber volume fraction, spindle speed, depth of cut and feed rate for the influenced machining force. From the table.5, fiber volume fraction is most significant parameter followed by fiber orientation angle, spindle speed, depth of cut and feed rate for influenced delamination factor of GFRP composite laminates. This work presented that effect of process parameters on surface roughness and delamination factor are almost same. It is observed from the above results, that the fiber volume fraction is most substantial contributed parameter to overall performance in all aspects on machinability of GFRP composites.

Table.3. Signal to Noise ratio for the surface roughness of GFRP

Levels	Factors				
	N	**f**	**d**	**ϕ_i**	**Ɵ**
1	-6.055	-5.895	-5.276	-5.233	-4.730
2	-5.252	-5.942	-5902	-5.043	-5.808
3	-5.570	-5.041	-5699	-6.601	-6.340
Delta	0.803	0.901	0.625	1.558	1.609
Rank	4	3	5	2	1

Table.4. Signal to Noise ratios for the machining force of GFRP

Levels	Factors				
	N	**f**	**d**	**ϕ_i**	**Ɵ**
1	-25.30	-25.75	-25.56	-25.11	-25.25
2	-25.75	-25.68	-25.47	-25.73	-25.65
3	-25.91	-25.51	-25.91	-26.10	-26.05
Delta	0.61	0.23	0.45	1.00	0.80
Rank	3	5	4	1	2

Table.5. Signal to Noise ratio for the delamination factor of GFRP

Levels	Factors				
	N	**f**	**d**	**ϕ_i**	**Ɵ**
1	-6.055	-5.895	-5.276	-5.233	-4.730
2	-5.252	-5.942	-5.902	-5.043	-5.808
3	-5.570	-5.041	-5.699	-6.601	-6.340
Delta	0.803	0.901	0.625	1.558	1.609
Rank	4	3	5	2	1

Table.6. S/N ratios of Responses for means of the surface roughness of GFRP composites.

Levels	Factors				
	N	**f**	**d**	**Ɵ**	**ϕ_i**
1	2.018	1.983	1.876	1.837	1.755
2	1.873	1.990	1.983	1.818	1.358
3	1.906	1.824	1.938	2.142	2.083
Optimum levels	N3	f4	D4	**Ɵ** 1	**ϕ_i** 1

Table.7. S/N ratios of Responses for means of the machining force of GFRP composites

Levels	Factors				
	N	**f**	**d**	**Ɵ**	**ϕ_i**
1	18.46	19.47	19.47	18.03	18.33
2	19.39	19.27	18.82	19.40	19.22
3	19.81	18.92	19.378	20.23	20.11
Optimum levels	N2	f4	D4	**Ɵ** 1	**ϕ_i** 1

Table.8. Signal to Noise ratio for the delamination factor of GFRP composites

Levels	Factors				
	N	**f**	**d**	**Ɵ**	**ϕ_i**
1	1.154	1.185	1.172	1.154	1.146
2	1.92	1.182	1.174	1.182	1.192
3	1.202	1.182	1.203	1.212	1.211
Optimum levels	N3	F5	D5	**Ɵ** 1	**ϕ_i** 1

Effect of process parameters on surface roughness, machining force and delamination factor based on response table: The influence of various machining process parameters on machinability of GFRP composite laminates will be studied by using responses, and revealed from figures.3, 4 and 5. And their main effects are shown in tables.6 to 8. Firstly, from the figure.3, it shows that the surface roughness increased with increasing the fiber volume fraction (from 40% to 60%) and fiber orientation angle (particularly from 45^0 to 90^0) and decreased with increasing the spindle speed, feed rate and depth of cut. Based on the main effect plot and response table to minimize the surface roughness, the optimum combination of each parameter set is N3 f4 d4 ϴ1 Φi1. From the figure.4, it is evaluated that the machining force is increased with increasing the fiber orientation angle, fiber volume fraction, spindle speed, depth of cut, and decreased with the feed rate. Based on the main effect plot and response table for reducing the machining force, the optimum level of each parameter set at N2 f 4 d4 ϴ1 Φi1. From the figure.5, it is observed that the delaminating factor increased with increasing the fiber volume fraction, fiber orientation angle, spindle speed and depth of cut where decreased with the feed rate. Based on the main effect plot and response table for reduction of delamination factor, the optimum level of each parameter set at N3f 5 d5 ϴ1 Φi1.

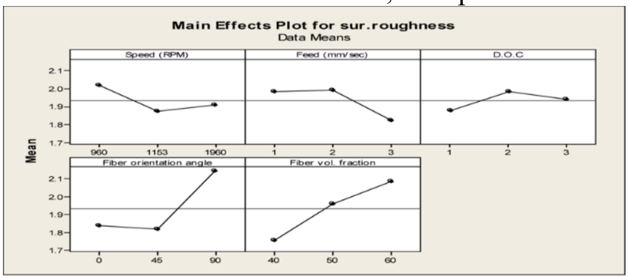

Figure.3. Illustration of factors effects on surface roughness

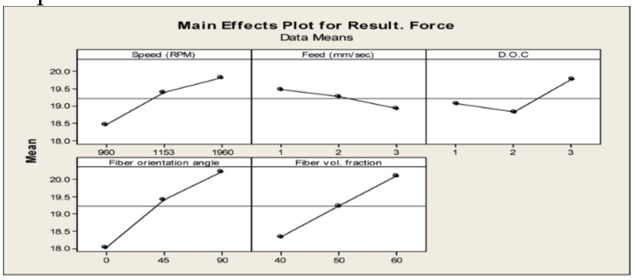

Figure.4. Illustration of factors effects on machining force

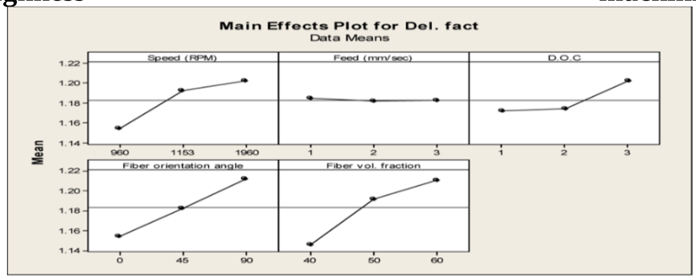

Figure.5. Illustration of factors effects on delamination factor

Tribological property: SEM Figure 6 a-b shows the evidence of fiber pull out and distorted cross section of fibers is the indication of the failure modes. Figure 6 c-d, displays the indication of rough cutting of fibers and fiber debonding or matrix cracking. This is likely formed where the machined workpiece have more fiber angle ply (fiber orientation increases from 0^0 to 90^0) as well as the fiber volume fraction is more (increases from 40% to 60%). At this stage, the movement of stylus tip of the surface roughness measurer shows the maximum surface roughness values. Therefore, the effect of increased spindle speed and feed rate results the maximum machining damages on machined surface. All of these noticed from parametric combination of N3 f 2 d1ϴ3 Φi3 (spindle speed is 1960RPM, the feed rate is 2mm/sec, depth of cut is 1mm, fiber orientation is 90^0, and fiber volume fraction is 60%).

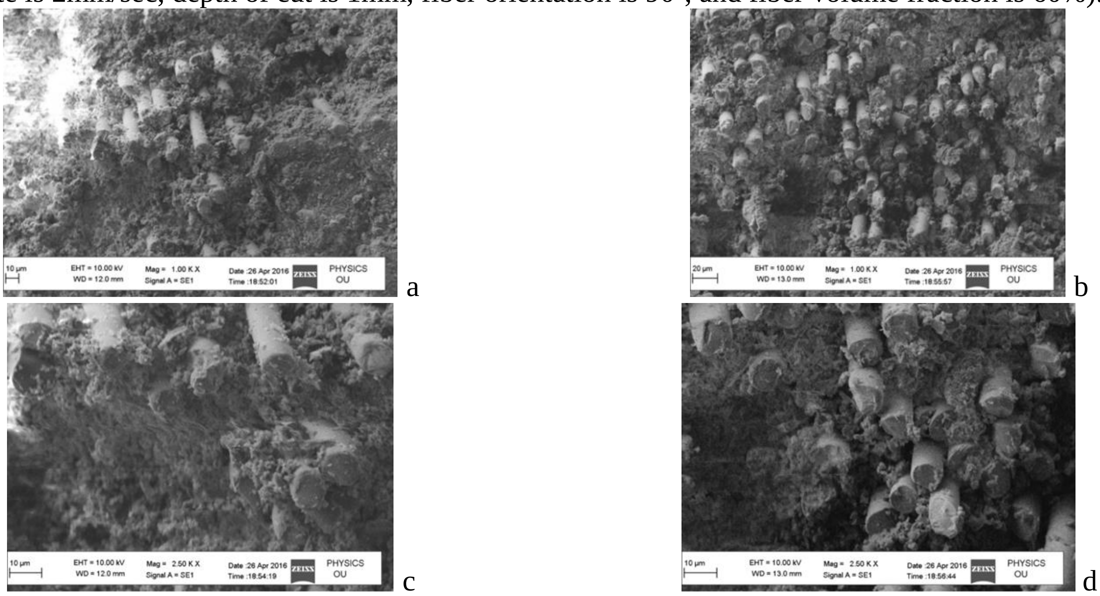

Figure.6 (a, b, c, and d). Scanning Electron Micrographs of Machined Surfaces

Analysis of variance (ANOVA) for GFRP composites: ANOVA is carried out from design of experiments and shown from tables.9 to 11. Firstly, from the table.9, it is established that input factor fiber volume fraction has statistical and physical significance (P=43.39%), for the surface roughness of machined GFRP composites. The error was found for ANOVA of surface roughness (R_a) is 10.17%. From the table.10, it is found that input factor fiber orientation angle has statistical and physical significance (P=36.91%), on the machining force. The error was found for ANOVA of machining force (F) is 12.91 %. From the table 11, it is observed that the input factor fiber volume fraction has statistical and physical significance (P=36.91%), on the delamination factor. The error was found for ANOVA of delamination factor (F_d) is 10.14 %. From the ANOVA tables the input factors fiber volume fraction and fiber orientation angle has more percentage contribution on surface roughness, machining force and delamination factor followed by spindle speed, the feed rate and depth of cut for milling of GFRP composite laminates.

Table.9. ANOVA for surface roughness

Factors	Sum of square	Degree of freedom	Mean square	'F' Test	Percentage contribution	Rank
N	0.10362	2	0.05181	0.71	5.56%	4
F	0.15980	2	0.07990	1.13	8.58%	3
D	0.05145	2	0.02572	0.34	2.76%	5
ϴ	0.86314	2	0.42157	3.94	29.54%	2
ϕ_i	1.236	2	0.61795	7.36	43.39%	1
Error	0.17026	24	0.0877		10.17%	
Total	2.58427	34			100%	

Table.10. ANOVA for machining force

Factors	Sum of square	Degree of freedom	Mean square	'F' Test	Percentage contribution	Rank
N	0.011580	2	0.005790	1.83	13.24%	4
F	1.417	2	0.709	0.27	2.17%	5
D	4.561	2	2.280	0.90	6.99%	3
ϴ	25.126	1	12.563	6.56	36.91%	1
ϕ_i	18.210	2	9.105	3.34	27.78%	2
Error	0.130122	24			12.91%	
Total	87.15187	34			100%	

Table.11. ANOVA for delamination factor

Factors	Sum of square	Degree of freedom	Mean square	'F' Test	Percentage contribution	Rank
N	0.011580	2	0.005790	2.13	15.06%	3
F	0.000056	2	0.000028	0.01	1.07%	5
D	0.005213	2	0.002607	0.87	6.78%	4
ϴ	0.019174	2	0.009587	2.95	27.73%	2
ϕ_i	0.030165	2	0.015082	4.27	39.22%	1
Error	0.0113254	24	0.007742		10.14%	
Total	0.079442	34			100%	

Validation tests by Multiple Regression Analysis (MRA): The correlation between input parameters (cutting speed, feed rate, depth of cut, fiber orientation angle and fiber volume fraction) and output responses (surface roughness 'R_a', machining force 'F' and delamination factor 'F_d'), during milling of UD-GFRP Composite laminates. And are examined by regression analysis with 27 runs of randomly selected sample size. From the following regression equation shows the values of surface roughness, machining force and delamination factor as,

(R_a)= -0.215+0.0054 ϴ +3.01N -0.000125 f (R^2=83.35%) ------------------(1)

(F)= 15.39+0.00256 ϴ +0.00245N-0.156f (R^2=95.94%) --------------------(2)

(F_d)= 0.235+0.000489 ϴ+0.00045N-0.325f (R^2=93.12%) -------------------(3)

Where 'Φi' is fiber volume fraction in percentage, 'ϴ' is fiber orientation angle in degrees, 'N' is cutting speed in Newton, 'f' is feed rate in millimeters per second and 'd' is depth of cut in millimeters. A comparison of experimental data with the calculated results from MRA within the reported range of average variations of 16.65%, 4.06% and 6.88% for R_a, F and F_d respectively.

4. CONCLUSION

This paper has presented and illustrated the end milling machinability results of GFRP composites using Taguchi's design of experiment. The following results are concluded based on the results of the investigational work.

- Fiber volume fraction plays most vital role on machinability of UD-GFRP composites. Milling with 60% of fiber volume content composites produces hazardous on machined surface in terms of surface roughness and damage factor. Better surface finish was achieved where machined composites have the fiber volume fraction is 40%.
- Fiber orientation angle is also significant factor on machinability of UD-GFRP composites. When the mill cutter fed along the fiber orientation (90^0) squeeze dominated fiber failure takes placed. Low surface

roughness and less delamination factor was arrived, where mill cutter edges fed along the direction of fiber orientation (0^0 and 45^0). Therefore, fiber volume fraction and fiber orientation angle are highly influenced factors fallowed by spindle speed, feed rate and depth of cut to minimize the surface roughness, machining force and delamination factor. Here the optimal parametric combinations are N3 f4 d4 ϴ1 Φi1, N2 f 4 d4 ϴ1 Φi1 and N3f 5 d5 ϴ1 Φi1 respectively.

- From the SEM micrographic observations it was showed that the machining damages (fiber-matrix debonding, subsurface damage and fiber cracks) progressively varying on mechanical behavior of composite laminates (fiber orientation and fiber volume fraction).

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