Investigation on machinability of GFRP composites by end milling using Taguchi's optimization technique

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Abstract— Machining of GFRP laminate materials are difficult task due to their anisotropic and non homogeneity in nature which consist of distinctly different phases. Machining of composite materials is rarely avoided in view of losing the strength of components due to fiber breakage and delamination. This paper discusses on the application of Taguchi's design of experiments, to explore the cutting parameters on machinability of unidirectional fiber reinforced polymer (GFRP) composite laminates. The design of experiments was conducted by using tungsten carbide end milling cutter at various spindle speeds, feeds and depth of cuts. . The macinability analyses of this selection of process parameters on glass fibre reinforced plastics are very important aspect in production industries such as automobile, aerospace and other applications. Moreover for better machining is to obtain by close dimensional accuracy with minimized surface damages, Taguchi analysis was carried out the signal to noise(S/N) ratio with analysis of variance (ANOVA) was utilized to analysis the effect of these process parameters on machinability of GFRP laminates. And thoroughly investigated to draw useful conclusions by SEM graphs and MINITAB15 software.

Key words- Glass fiber reinforced composite laminates, End milling, Machinability, Tool life, Taguchi's method, SEM graphs

I. INTRODUCTION

Milling of glass fiber reinforces plastic composite materials appreciably affected by delaminating damage and poor surface finish under the action of machining process parameters and cutting forces and blunt tool cutting edge. For this reason to improve the machinability and minimize the damages, interlayer fracture, splintering and fiber/ resin pull out. The ability of secondary machining of FRP materials depend on many aspects such as physical properties, fiber types, fiber orientation, variability of matrix material and fiber volume fraction . Any secondary processed FRP materials to get the closer dimensional accuracy and geometrical shapes operations in a specified manner, for minimization of damages is very important in terms of reduce the wastage of time and improvisation of production quality In this connection, to conduct the number of experiments by design of experiments to reach a specific delaminating factor and good surface finish. Now-a-days glass fiber reinforced plastics (GFRP) are identified having the excellent properties such as high strength to weight ratio, high stiffness, high specific modulus of elasticity, good thermal and corrosion resistance, which makes widely used in aerospace and air craft applications . But fpr composites have non-homogenity, anisotropic nature, irregular and rough textures presence on the work piece Bhatnagar [1]. During machining the abrasive nature of glass fibers causes severe wear takes place in cutting edges in the tool Santanakrishnan [2]. The accurate machining is also presents to performing the good dimensional accuracy Ferreira [3]. Koplev etal [4],Kaneeda [5], Pau and Hocheng[6] studied how the fiber orientation effect on the surface integrity and tool wear rate, moreover selection of process parameters and tools are depending on the types of fibers arrangement in composites and which is very useful in machining process. Hakeemuddin ahmed [7] investigated to determine the relationship between spindle speed and feed which minimizes the surface roughness and delamination factor. The variation of the cutting forces involved is also studied in relation with the process variables and correlated with tool wear to derive by the regression equations. Reddy srinivasulu [8] investigated on influence of cutting process parameters on surface roughness and delamination factor on GFRP during end milling , Taguchi method is used to investigate the machining charecteristics of GFRP and results of ANOVA finally concluded by using artificial neural network. Rahman et al.[9] studied the machinability of CFRP composites with various cutting parameters with three types of cutting tool materials, namely uncoated carbides, ceramic and Cubic Boron nitride (CBN). It was reported that the carbide tool performed better at low cutting speeds, whereas the performance of CBN tool surpassed the others at high cutting speeds. Palanikumar et al [10] got experimently measurement of surface finish in FRP is less affected compare to that in metals, because of FRP arrangement may cause to errors it will also cause the fiber stacks on the stylus. On the other hand, varying the process parameters to get the the optimal tool wear or life is influenced by cutting speed [11, 12].

II. EXPERIMENTAL SETUP

A. Schematic of machining-

The work piece material selected for investigation is (+45/- 45)uni- directional (UD) glass fiber reinforced polyester plastic composites fabricated by hand layup compression molding technique of 60%fiber and 40%of polyester resin . The work pieces are cut by diamond abrasive wheel by size of 100mmx100mmx10mm dimension. In this study, the experiments are carried out on a conventional universal milling machine incorporated by high speed spindle motor 10Hp to perform slots on work pieces using solid carbide end mill cutter. Here the machining component forces are (F_X-feed force, Fy-cutting force and F_z-Thrust force, Here total machining force 'F' is obtained by $F = \sqrt{F_x^2 + F_y^2 + F_z^2}$) were obtained by mill tool dynamometer with the range of force measurement in co-ordinate direction 0 to 50 Kgf.. The surface roughness was measured measured along the cut slot from Mitutoyo profiler the cutoff value and transfer length were set as 0.5mm/sec 5mm while take the centerline average (R_a), of three different places readings are taken to obtain the precision data. In addition the cutting speed (rpm),feed (mm/sec) and depth of cut (mm) are controlled input parameters in this investigation. Each experiment was conducted three times and finds the delamination (W_{max}) around the each slot at three places by using travelling microscope with magnification of 200X. The average flank wear heights were measured by optical stereo microscope using UTHSC image tool software. The tool life of end mill cutter edge was evaluated by average flank wear value 0.3mm on cutting edges. Take the average value is final value for calculation part for each experimentation.

B. Taguchi experimental design and selection of parameters-

Extensive and expensive experimentations would typically be required to evaluate the machinability of a material. Hence, experimental approach of machinability assessments can be well achieved through statistically designed tests or series, 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. Taguchi method systematically plans the experiments according to a specially designed orthogonal array (OA) which can significantly reduce the number of experiments [13]. In Taguchi's OA, each combination of factors has a balance, in which within a column of the array, each factor has equal number of levels. Physical properties of fiber reinforcements and the matrix material, fiber orientation, types, matrix material and volume fraction greatly influence the machinability of GFRP composites apart from processing parameters which includes cutting speed, feed rate and depth of cut, tool materials and geometries. Such a large number of influencing factors inevitably add to the complexity of experimental investigations. Hence, in this part of work, only machining or processing parameters were considered for the parametric analysis of their significant influence. Here different combinations of machining parameters namely cutting speed N and feed rate f and depth of cut, that effects on the surface roughness, machining force, tool life and delaminating factor. The range of machining conditions were selected to owing the importance of industrial applications, within the limit of the machine tool as well as over the range of conditions employed. In the traditional full factorial experimentation, 27 trials would be needed to complete the entire experimental work of three factors at three levels. However, based on the selected parameters and their levels, current parametric study could be well performed using the L_9 Taguchi OA in which nine experimental runs would be required to complete the array. In the Taguchi analysis, 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. However, in this paper, S/N ratio was chosen for the Taguchi analysis because S/N ratio can represents both the average (mean) and variation (standard deviation) of the experimental results. Hence, depending on the qualitative characteristics of the experimental response, the S/N ratio can take up either 'the lower the better' or 'the higher the better' category respectively. A robust quality of a characteristic always corresponds to higher value of S/N regardless of the category.

			Levels		
Process Parameters	Units	Notation	1	2	3
Spindle speed	RPM	N	1153	1950	2500
Federate	mm/sec	f	1	2	3
Depth of cut	mm	d	1	2	3

Table1. Process control parameters and their levels

Exp no	Speed	Feed	D.O.C	Surface roughness(R_a) In µm	S/N R_a	Resultant Force In Newtons	S/N F	Tool life (TL) in sec	S/N TL	Delaminating Factor(F_d)	S/N F_d
1	1153	1	1	2.016	-6.519	21.60	-27.6	630	-55.6	1.234	-2.146
2	1153	2	2	2.126	-7.241	22.40	-27.1	589	-55.1	1.340	-1.245
3	1153	3	3	2.132	-6.025	25.40	-26.5	648	-54.3	1.268	-0.354
4	1950	1	2	2.215	-5.948	21.10	-25.8	702	-50.3	1.206	-1.235
5	1950	2	3	2.321	-6.842	22.01	-26.4	732	-56.2	1.301	-1.650
6	1950	3	1	2.234	-6.012	22.13	-23.4	587	-51.6	1.268	-2.349
7	2500	1	3	2.128	-7.125	22.32	-27.3	365	-55.3	1.024	-2.104
8	2500	2	1	1.998	-8.014	20.13	-26.7	324	-53.5	1.028	-1.697
9	2500	3	2	1.995	-7.114	20.34	-25.9	348	-52.4	1.135	-1.578

Table2. Test factors and their levels with S/N ratio for all outputs

C. Measurement of Surface roughness resultant machining force, tool life and Delamination factor-

Forces acted on the cutting tool which can be measured by a mill tool dynamometer with data acquisition system and processed on a personal laptop. The surface roughness was measured with Talysurf for knowing the surface quality cutoff value and transfer length were set as 0.5mm/sec 5mm. The tool life of solid carbide cutter was evaluated by optical stereo microscope on average flank wear of 0.3 mm on the cutting edges. The computation of the delamination was done by the measurement of the Maximum width of damage (Wm_{ax}) affected by the material, the damage normally allocated by delamination factor (Fd) was resolved. 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 achieved by the following equation: $Fd= (W_{max}/ W)$. W_{max} is the maximum width of the damage in mm and 'W' is the width of cut in mm. All the above measurements are repeated three times to check for the consistency.

Fig 1. Machining of GFRP laminate plate is properly fixed in machining center by special designed fixture with data acquisition laptop attachement

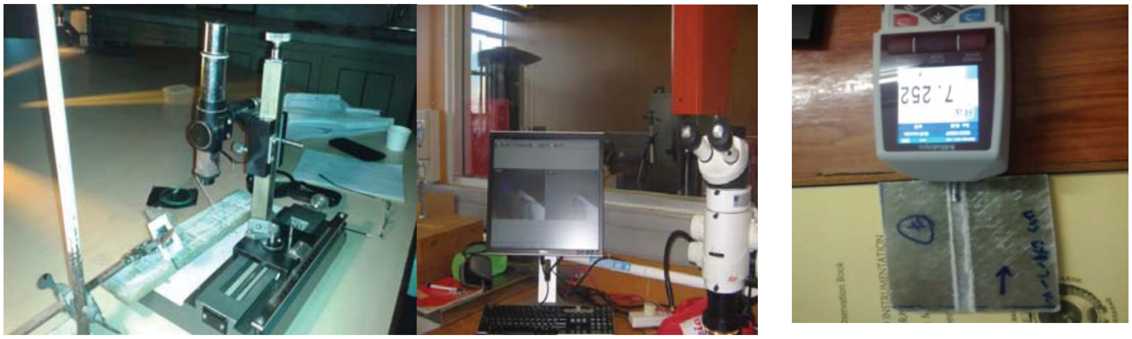
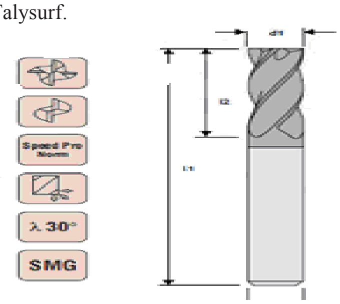


Fig 2. (a) Measurement of delamination damage using Travelling Microscope (b). Measurement of tool wear rate by stereo microscope (c). Measurement of surface roughness by Mitutoyo Talysurf.



FM Star (45 HRC) Flat End Mills - Regular Series							
Article No.		Dimension (mm)					
2 Flute	4 Flute	Ø d1 h10	Ø d2 h6	l2	l1	Uncoated	TiAlN Coated
H-SEM2080L	H-SEM4080L	8	8	25	75	□	■

Fig3. Solid carbide tool (from tool manufacturer's catalogue)

III. RESULTS AND DISCUSSION

The results of the milling tests allowed the evaluation of the GFRP composite material manufactured by compression moulding hand-layup technique used with solid carbide end mill of 10mm diameter. The Machinability was evaluated by surface roughness (Ra), resultant force (F), tool life (TL) and delamination factor (Fd).

A. Influence of the cutting parameters on the output responses based on S/N ratio, Responses and ANOVA-

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 the results of Taguchi analysis (S/N ratio) for surface roughness (Ra), resultant force (F), tool life(TL) and delamination factor (Fd) using the approach of smaller is better. From the figure4, 5, 6 and7; The response graphs, it is depicted that desirable combination for low surface roughness and high tool life is at high cutting speed and low depth of cut. From the all graphs it is observed that cutting speed and depth of cut have more influenced parameters on surface finish compared to the depth of cut. On other hand, the use of high speed and low depth of cut justify to produces decreasing the delamination factor and resultant machining force.

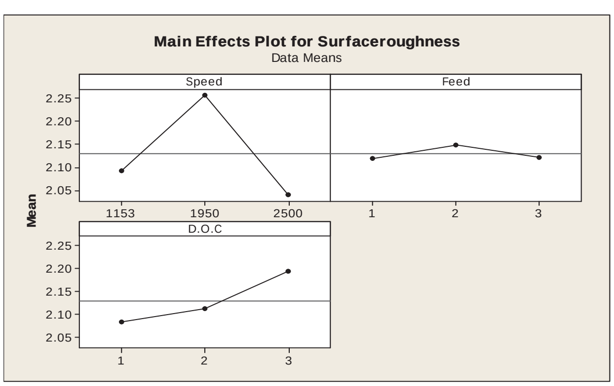


Fig 4. Illustration of factors effects on surface roughness

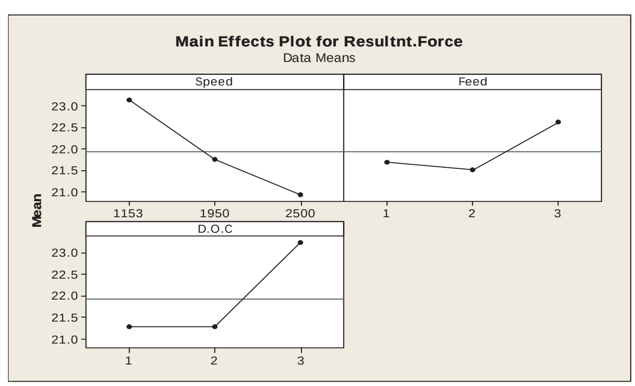


Fig 5. Illustration of factors effects on resultant machining force

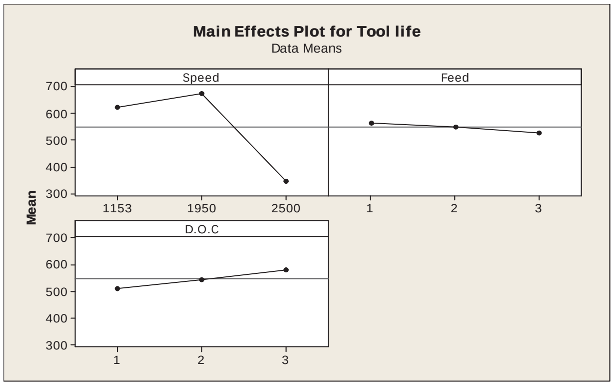


Fig6. Illustration of factors effects on tool life

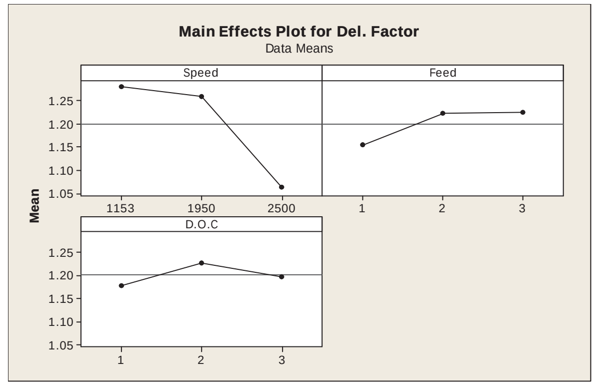
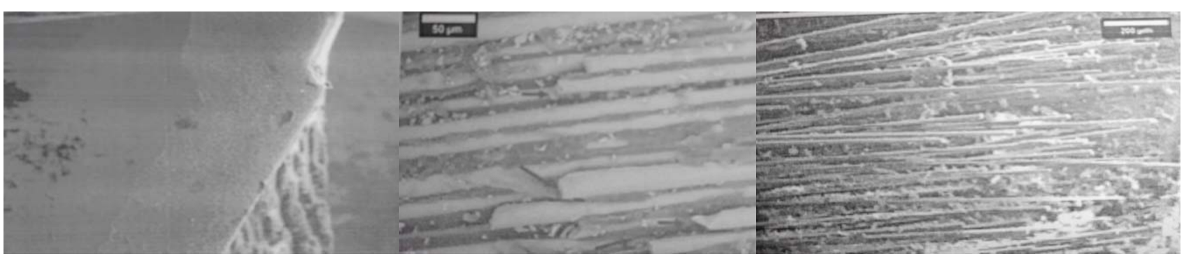


Fig 7. Illustration of factors effects on delamination factor

Eventually, the results represent in (ANOVA) table3, the cutting speed and depth of cut has high statistical and physical influences on resultant forces at 95% confidence level. The depth of cut increases the number of layers of fibers is to be cut increases, considerably machining forces are also high. From previous study [14] observed that cutting speed and depth of cut is most important factors which effects on machinability. In this research work, it is shown that unlike turning, the depth of cut is important factor influencing the tool life. The combinations of cutting speed and depth of cuts are most governing factors on surface roughness and tool life, although increasing the spindle speed tool wear and reduces the toll life. The narrowed cutting edge of the tool imaged by SEM graph is evident for flank wear to be vital role in tool wear mechanism observed in this work. From the fig 8, the feed rate and depth of cut are increases the tool continuously moving, splitting occurs in front of the tool edge and chip fails its continuity, chip break will not occur and increases chip thickness, so therefore surface delaminating will takes place. On other hand, Fig. b-c shows the indication of fiber extraction and breakage from machined surface or matrix failure also evident floury chips besides the breakage of fibers.



(a) **(b)** **(c)**

Fig 8. **(a)**SEM image of tool wear that indicates the flank wear on one of cutting edges
SEM graphs for machined quality (b) Fiber pull out (c) Matrix cracking

Now from Taylor's extended tool life equation we get;
V x T^ n x f^ n1 x d^ = K
Where T=Tool life in min, f= Feed in mm per second, d= Depth of cut in mm, n= Tool constant for solid carbide tool-0.25(from tool manufacturers data book), n1= Feed exponent constant=0.5(from tool manufacturers data book), n2=Depth of cut exponent constant-0.20 (from tool manufacturers data book) K=Constant-47(from tool manufacturers data book)
nw sample calculations of tool life for first run:
T = (k^1/n)/(V^1/n x f^n1/n x d^n2/n)
Putting the values of n, n1, n2, k in above equation tool life equation becomes,
T = k^0.25 /(V^0.25 x f^2 x d^0.8)
T= 47^O.25 /(1153^0.25 x 1^2 x 1^0.8)= 630min

Tool life model was obtained from and the significance of these variables is judged by statistical analysis. [15].

RESPONSE	SS	DF	MS	F	%CONTRIBUTION
Surface roughness, Ra					
N	0.076736	2	0.038368	8.70	55.64
f	0.01215	2	0.00607	0.05	5.45
d	0.05985	2	0.00993	5.71	35.21
Error	0.011932	4	0.00596	1.35	3.70
Total	0.160668	10			100
Resultant force, F					
N	7.444	2	3.722	1.93	58.24
f	1 .160	2	0.580	0.38	6.54
d	5.683	2	2.842	2.03	32.67
Error	0.9215	4	0.46075	0.21	2.55
Total	15.3935	10			100
Tool life, TL					
N	186764	2	93382	38.93	84.29
f	2172	2	1086	0.03	2.16
d	6940	2	3470	0.11	10.35
Error	3214	4	1607	0.01	3.2
Total	199090	10			100
Delaminating factor, F_d					
N	0.086584	2	0.043292	14.09	65.35
f	0.00943	2	0.00472	0.30	26.29
D	0.00383	2	0.00192	0.11	5.34
Error	0.00125	4	0.00625	0.065	3.02
Total	0.101094	10			100

Table 3. ANOVA for all machinability characteristics based on S/N ratio

NOTE: SS: Sum of squares; DF: Degree of freedom; MS: Mean squares; F: Fisher test

IV. CONCLUSION

From the experimental results presented the following conclusions are made by milling of uni-directional GFRP composite laminate plates with solid carbide end mill cutter carried out by Taguchi's L_9 orthogonal array. This quality parametric study of experimentation has been performed by using response graphs, tables and statistical analysis of variance.

1. When the Cutting speed is increases surface roughness and delamination factor decreases, but depth of cut increases continuously will hazards on machinability characteristics of GFRP composite laminates. SEM graphs were used to observe the surface integrity and morphology of machined GFRP composite laminates.
2. The experimental results shows that in milling, the spindle speed has highest statistical influence on tool life (84.29%), delamination factor (65.35), resultant force (58.24%) and surface roughness (55.64%). However, feed rate is insignificant on surface roughness, resultant force and tool life.
3. Spindle speed=1153Rpm, Depth of cut=1mm and feed rate=1 mm/sec produces optimal values for obtaining the better tool life. Spindle speed=2500Rpm, Depth of cut=1mm and feed rate=1 mm/sec recommended values for obtaining the better surface roughness, Spindle speed=2500Rpm, Depth of cut=1mm and feed rate=2 mm/sec produces optimal values for reducing the cutting forces, hence the power consumption will also reduces. Spindle speed=2500Rpm, Depth of cut=2mm and feed rate=2 mm/sec produces optimal values for reducing the surface delamination.
4. An decreased cutting speed, feed rate and depth of cut decelerates the the tool wear rate and this leads to increasing the tool life. The derived Taylor's equations have established that the life of the cutting tool is strongly effected by cutting speed and depth of cut.
5. ANOVA results shows that cutting speed and depth of cuts are most governing factor effecting the resultant forces in milling of GFRP composite laminates, distant from the feed rate.

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