DOI: https://doi.org/10.24425/amm.2024.151431

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AN EXPLORATORY STUDY OF THE SURFACE INTEGRITY OF VARIOUS FRP COMPOSITES IN FACE MILLING OPERATION

The use of glass, carbon and hybrid /glass/carbon epoxy polymer composites is widely used in the automotive, manufacturing and aerospace sectors. Milling is a secondary production process in which the final shape of the product is produced with the desired shape and high dimensional accuracy. The objective of this study is to enhance our knowledge of the machinability properties of composite materials in the secondary manufacturing industry. In this research study, performing face milling operations with different tools on bidirectional (BD) glass, unidirectional (UD) glass, carbon/epoxy, and glass/carbon/epoxy (hybrid epoxy) polymer composites. This experimental work derives conclusions that contribute to the improvement of the milling process for better surface quality. Taguchi's L16 Design of Experiments (DOE) and Analysis of Variance (ANOVA) are used to determine the effect of tool type, speed of spindle, rate of feed, cut depth on surface roughness and delamination factor. And it was concluded that glass/carbon hybrid epoxy polymer laminates showed improved surface quality when milled with a Poly Crystalline Diamond (PCD) tool at parametric combinations of rate of feed is 300 mm/min, speed of spindle is 1000 rpm, and cutting depth is 0.5 mm. In addition, the experimental results of the scanning electron microscope examination were also verified. And found excellent machined surface quality and least damage with the above optimal process parameter combinations.

Keywords: Glass; carbon and hybrid composites; Milling tools; surface integrity; ANOVA; Scanning Electron Microscope (SEM)

1. Introduction

Fiber reinforced composites (FRP) outperform traditional metallic materials in terms of specific strength and corrosion resistance. These have shown to be effective engineering materials and are frequently replacing standard metallic materials with ones that perform better. Consequently, composites of polymer have been widely replaced by general metallic materials in aerospace, automotive, and marine applications [1]. In aerospace and military satellites, carbon fiber reinforced composites (CFRP) are widely used to manufacture structural parts [2]. Polymer composites are anisotropic and present a number of challenges for designers to adopt appropriate machining practices [3]. Fiber pull-out and delamination failures lead to deterioration of the milled surface, even the reinforcement orientation is disturbed due to milling cutting reaction forces and poor component strength [4]. Conventional material milling is a well-known machining process for composite materials in many industries [5]. There is a need to optimize input control factors such as material of the tool, speed of spindle, rate of feed, cut depth to achieve better milled surface perfection with minimal damage [6].

And it is essential to know the cutting mechanism and tool configuration to minimize surface roughness, machining forces and delamination damage in the secondary processing industry [7]. Authors performed edge trimming procedures with varied input parameters on CFRP composite laminates and found that milling is required to produce a completed product in an almost clean shape with better surface perfection. In this regard, he experimented with three different types of micro-grain carbide tool cutting edges (numbers 2, 4, and 6). Additionally, using the Taguchi's technique, acceptable milled perfection was discovered at greater rates of machining is 150 m/min, low rate of feed is 0.05 mm/rev, and six fluted face milling tools [8] and [9].

Previous studies investigations are aimed at achieving better results and continuous improvement using statistical analysis (ANOVA) in the machining of polymer composites [10] and [11]. PCD tools are frequently utilized in the current environment to reduce tool wear and machining damage issues in order

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to improve machined surface topography [12] and [13]. When milling CFRP composites, the material of the tool and choice of the appropriate tool nomenclature are also important in achieving the desired machined surface perfection. Industrial applications effectively exploit the design and fabrication of diverse tool signatures of machining tools [14].

On the other hand [15] investigated the damage mechanisms in the milling of GFRP composites utilizing two, three, and four fluted end milling tools with varying machining process parameters by employing an artificial neural network (ANN) technique. Because there is more rubbing action at the tool-work piece interface when using low-numbered cutting lipped tools, they see an inter-laminar shear failure at higher feed rate and cutting speed values. A comparative study [16] comparing the use of three different end mill tools – solid carbide K-10, sharp edged carbide, and Ti-Namite carbide K-10 – for the machining of GFP laminates came to the conclusion that the use of sharp edged carbide end mill tools could result in higher machinability characteristics.

The machining procedures of different FRP composites have been studied in the literature, and it has been found that tools made of carbide coated, tungsten carbide, PCD, and high speed steel (HSS) are effective for producing superior surface quality. Surface roughness, machining forces, and workpiece degradation (deformation, interphase flaws, die fracture, debonding, etc.) are the key issues. Several studies have attempted to optimize variable level factors to reduce catastrophic failures in FRP milling using Taguchi's Design of Experiments (DOE) and other modeling data.

According to a review of the literature, numerous researchers have used Taguchi and ANOVA in their machining processes to optimize the parameters of the cutting process in order to provide superior surface quality. Most of the research was conducted using generalized milling tools on a range of work pieces, with a small number of specially built tools with different tool angles. That restriction was noted in earlier research. It's essential to minimize labour costs in order to implement the latest trends and enhancements. Therefore, the goal of this work is to develop a novel method for analyzing composite laminates made of carbon, BD-glass, UD-glass, and hybrid/epoxy polymer by creating and optimizing a set of process input parameters utilizing Taguchi's L16 DOE and a separate tool for milling materials with distinct tool signatures.

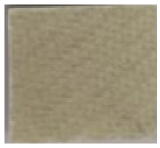
2. Materials and method

2.1. Workpiece specification

Workpiece samples (BD-woven roving-GFRP $[0°/90°]_{10}$, UD-woven roving-GFRP $[\pm45°]_{10}$, UD-woven roving-CFRP $[\pm45°]_{10}$ and UD-woven roving- glass/carbon hybrid epoxy polymer composite laminates are produced using a hand press lamination technique [17]. Each sample of composite laminates was fabricated by mounting 10 layers of 400 mm long × 400 mm wide × 10±6 mm thick mold panel. K-6 hardener and L-12 epoxy resin are used in the manufacture. Each sample was layered into a mould at a ratio of 10:1 between epoxy resin and hardener, and the resulting mixture was then poured into the mould at a pressure of 200 kgf/cm^2 to roll the fiber/matrix composition evenly. After this process is completed, the resin is cured for 8 to 10 hours at room temperature. Performing all face milling operations on a Computer Numerical Control (CNC) milling machine. The average volume of fibers "V_f," in the composite laminates mentioned above was found to be 55%, as per ASTM D2548-68. Burnout tests were performed where 2.5 mm × 2.5 mm samples were sized and weighed before being placed in the furnace and fired. Now the weight of the samples was checked and the fiber volume was measured after the matrix was fired. This process is repeated for all types of FRP composites and the obtained compositions of different composites are shown in TABLE 1.

TABLE 1

Composition of different composite work pieces

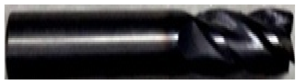
Volume fraction (%) resin and reinforcement of fiber				
Type of work piece	**% E Glass Fiber**	**% Carbon Fiber**	**% Epoxy**	**Work piece view**
BD-Glass/ epoxy composite	60±5	0	40±5	
UD-Glass/ epoxy composite	60±5	0	40±5	
Carbon/ epoxy composite	0	60±5	40±5	
Hybrid composite	30±5	30±5	40±5	

2.2. Specifications of milling tools

In this work, milling operations were performed with four types of 10 mm diameter face milling tools, (i) Conventional HSS milling tool with four cutting edges with a face angle of 30° and a back angle of 10° (ii) Conventional solid carbide milling tool with four cutting edge angles edges of 30° and angle of clearance of 10° (iii) Customized two-flute carbide tool with angle of rake 35° and angle of clearance 14° (iv) Conventional PCD milling tool with four angle of rake 36° and angle of clearance 12° were considered for experiments to reveal a comprehensive assessment in milling operations. Tool specifications and images of the four types of tools are shown in TABLE 2.

TABLE 2

Experimental factors and levels and details of different type of tools

Variable input parameters	I	II	III	IV	
Tool Type	**HSS tool**	**Solid carbide tool**	**Two fluted carbide tipped tool**	**PCD tool**	
Work piece type	BD-Glass/Epoxy	UD-Glass/Epoxy	Carbon/epoxy composite	Hybrid/epoxy composite	
Spindle speed ‘‘N’’ (rpm)	1000	2500	4000	5500	
Feed rate ‘‘f’’ mm/min	100	200	300	400	
Depth of cut ‘‘t’’ mm	0.25	0.5	0.75	1	
Technical specifications of the tools used for experimentation					
Cutting tool	**Taguchi’s cutting tool code**	**Diameter in ‘‘mm’’**	**Rake angle**	**Clearance angle**	**Tool view**
HSS tool	1	10	30	10	
Solid carbide tool	2	14	30	10	
Customized two fluted carbide tipped tool	3	10	35	14	
PCD end milling tool	4	10	36	12	

3. Experimental procedure

On a CNC milling machine with a 7.5 kW spindle control and a maximum spindle speed of 7500 rpm, face milling operations were carried out. The cutter rotates against the direction of feed rate of the workpiece and is up-cutting. Fig. 1, the experimental setup is depicted. Taguchi L16 orthogonal array (OA) was considered to perform the experiments shown in TABLE 3. Five factors at four levels ($4 \wedge 5$) OA were planned using Taguchi DOE, here are the input factors (cutting tool code A, workpiece code B, spindle speed code C, feed rate code D, and depth of cut code E). And the parameters are provided in TABLE 3 and each has four levels.

According to Taguchi’s investigation, the average value of the experimental results and the corresponding signal to noise (S/N) ratio. Mean (mean) and variance are the terms used to define the S/N ratio of Taguchi analysis (standard deviation). The lowest surface roughness and delamination factor can be achieved with optimal process input parameters. The Signal to Noise ratio will therefore be categorized under “smaller the better.” At three different positions along the instrument travel route on the vertical slot wall, at the start, middle, and end points,

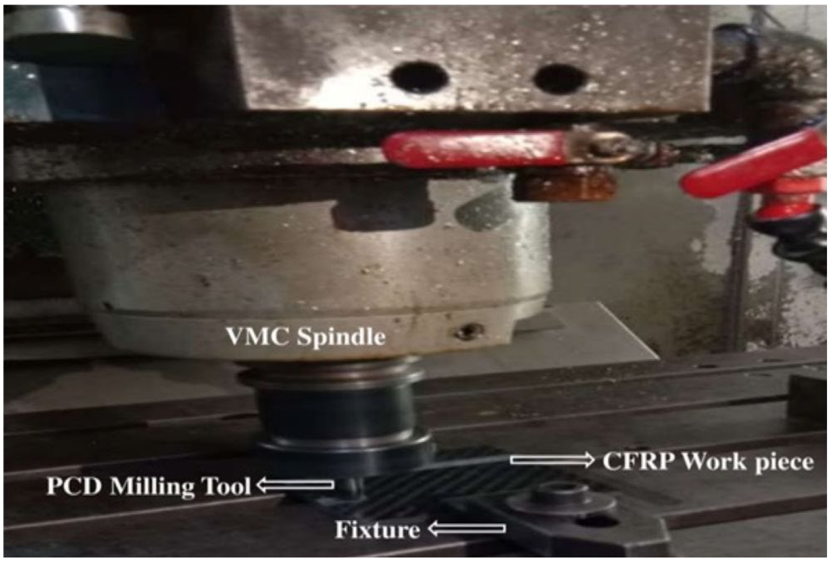


Fig. 1. Experimental set up

TABLE 3

Experimental factors and levels and details of different type of tools

Exp. No.	Cutting tool code	Work piece code	"N" (rpm)	"f"(mm/min)	"t" (mm)	Surface roughness (Ra) (µm)		Delamination factor (F_D)	
	(A)	(B)	(C)	(D)	(E)	(Ra) (µm)	S/N (dB)	(FD)	S/N (dB)
1	1	1	1000	100	0.25	3.64	–9.21	1.69	–4.565
2	1	2	2500	200	0.5	3.68	–8.911	1.84	–3.784
3	1	3	4000	300	0.75	4.1	–8.059	1.9	–3.687
4	1	4	5500	400	1	3.35	–8.458	1.23	–4.112
5	2	1	2500	300	1	3.54	–8.521	1.69	–4.747
6	2	2	1000	400	0.75	2.95	–8.589	1.77	–4.501
7	2	3	5500	100	0.5	3.94	–8.358	1.82	–3.862
8	2	4	4000	200	0.25	2.89	–8.814	1.76	–4.524
9	3	1	4000	400	0.5	2.54	–9.319	1.84	–3.568
10	3	2	5500	300	0.25	2.87	–9.113	1.8	–3.147
11	3	3	1000	200	1	2.64	–9.21	1.78	–4.408
12	3	4	2500	100	0.75	2.87	–9.064	1.74	–4.41
13	4	1	5500	200	0.75	2.6	–9.219	1.69	–4.742
14	4	2	4000	100	1	2.24	–9.824	1.4	–4.907
15	4	3	2500	400	0.25	1.63	–10.37	1.21	–4.976
16	4	4	1000	300	0.5	1.56	–11.32	1.1	–5.055

accurate surface finish was taken into account for surface roughness measurements and readings. As well as all values were measured by surface roughness tester (Mitutoyo make Surf test SJ-210 Series). The Center Line Average (CLA) method was considered as a cut-off of 0.5 mm for a length setting of 2.5 mm according to ISO 4287/1 with a surface accuracy of 10 µm. To measure the delamination factor (F_D), the moving microscope was calculated as 0.01 mm, and the average value by vernier scale from Eq. (1) was according to experimental calculations [18].

The delamination factor was measured using the formulas,

$$FD = W_{\mathrm{Max}}/W \tag{1}$$

Where W – Actual cutting width of the tool. W_{Max} – Machined groove width.

4. Results and discussion

4.1. Effect of variable input factors on output responses using statistical analysis and SEM analysis

4.1.1. Statistical analysis

The Taguchi matrix of experimental combinations is used to find the best way to simplify the control factors. The aim of this work is to establish the best milling surfaces by employing Taguchi design of trials to optimize variable input parameters. The workpiece type, spindle speed, rate of feed, cut depth and varied tool geometries are taken into consideration as input factors. Measurable quality traits include surface roughness and damage factor.

TABLE 3, details the numerical values of the variable input factors and measurable outcomes for the L16 (OA) experimental setup. TABLE 3 and TABLE 4 present the ANOVA results of mean S/N values for surface roughness and delamination factor and the percentage contribution of each input factor. The S/N analysis suggests that the PCD milling tool performs better on all four types of workpieces. And the optimal parametric combinations (A4 B4 C1 D3 E2) for surface roughness and delamination were found to be 1.56 µm and 1.1

The statistical indicator of how well the observed values fit the expected values is called R-squared. A 95% confidence level was considered for the experiment (ANOVA at a significant level of $p = 0.05$). The confidence level also decides the obtained p-value from the ANOVA answer TABLE 4.

Here, the main effects plots are presented using MINITAB 17 to determine the impact of various levels of testing on the output replies. In the main effects graphs, a line connected the mean value for each experiment level. Figs. 2 and 3 display the main effect plots for surface quality and the delamination factor, respectively. The experimental data were subjected to an ANOVA, and the outcomes are displayed in TABLE 4.

The result in TABLE 4 shows that tool variety has a significant impact on the output parameters. Tool variety is ranked first, followed by feed rate and spindle speed. Depth of cut and workpiece material are ranked four and five, respectively. The ANOVA outcomes for surface finish, percentage contribution for tool type, workpiece type, and speed of spindle, rate of feed and cutting depth are 71.5%, 4.8%, 5.9%, 10.4%, and 1.8%, respectively.

ANOVA results for delamination factor, percentage contribution for tool type, workpiece, speed of the spindle, feed speed, and cutting depth are 67.8%, 10.5%, 4.6%, 7.8%, and 4.4%, respectively. Where tool type comes first, workpiece type and feed rate come second and third, speed of spindle and cutting depth are classified as four and five.

TABLE 4

ANOVA results for surface roughness and delamination factor

ANOVA results for Surface roughness							
Parameters code	**Milling process parameters**	**Degree of freedom**	**Sequential sum of squares**	**Means of squares**	**F-ratio**	**P-Value**	**Percentage contribution**
A	Tool type	2	5.825	2.9125	15.25	0.0124	71.50%
B	Work piece type	2	0.5008	0.2504	0.83	0.642	4.80%
C	Spindle speed	2	0.8442	0.4221	1.12	0.496	5.90%
D	Feed rate	2	1.8692	0.9346	2.16	0.252	10.40%
E	Depth of cut	2	0.2406	0.1203	0.38	0.957	1.80%
Error		5	0.8252	0.4126			5.60%
Total		15	10.105				
S = 0.0750624, R-Sq = 97.49%, R-Sq (adj) = 81.2%							
Tabulated F-ratio at 95% confidence level $F_{0.05;\,1;\,6} = 5.99$, $F_{0.05;\,2;\,6} = 5.14$							
ANOVA results for Delamination factor							
A	Tool type	2	4.251	2.1255	13.86	0.018	67.80%
B	Work piece type	2	1.1253	0.56265	3.26	0.061	10.50%
C	Spindle speed	2	0.2168	0.1084	1.02	0.248	4.60%
D	Feed rate	2	0.6258	0.3129	2.1	0.645	7.80%
E	Depth of cut	2	0.3025	0.15125	1.25	0.502	4.40%
Error		5	0.9562	0.4781			5.10%
Total		15	7.4776				
S = 0.062141, R-Sq = 88.24%, R-Sq (adj) = 80.5%							
Tabulated F-ratio at 95% confidence level $F_{0.05;\,1;\,6} = 5.99$, $F_{0.05;\,2;\,6} = 5.14$							

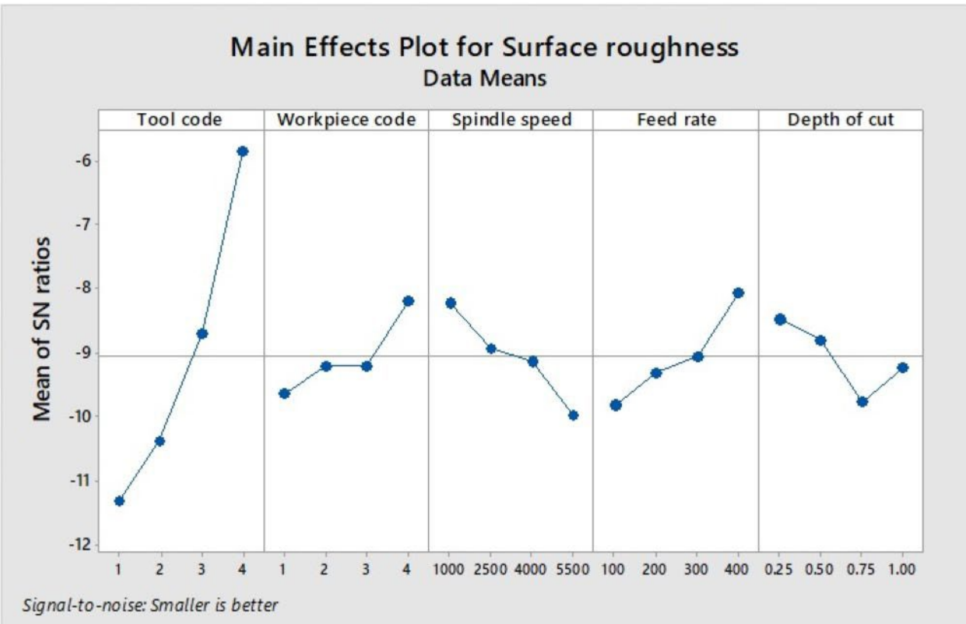


Fig. 2. Mean S/N graph for surface roughness

For tool type, the obtained p-value for surface roughness and delamination factor is less than 0.05; this is an indication of high tool effect rather than other parameters. The confidence level in the regression model for surface finish and delamination factor is also 97.49% and 88.24%. Additionally, it demonstrates that this model is affected by interactions.

Additionally, Fig. 5 illustrates how different process factors interact to affect the delamination factor. The tool type has the strongest relationships with the other variables. Similar to this, additional process variables such as speed, feed, depth of cut, and workpiece have a significant interaction influence on the delamination factor. From the example above, it is evident that the type of tool (material of the tool and tool signature) is statistically important for attaining the intended results (lower values of surface roughness and delamination factor).

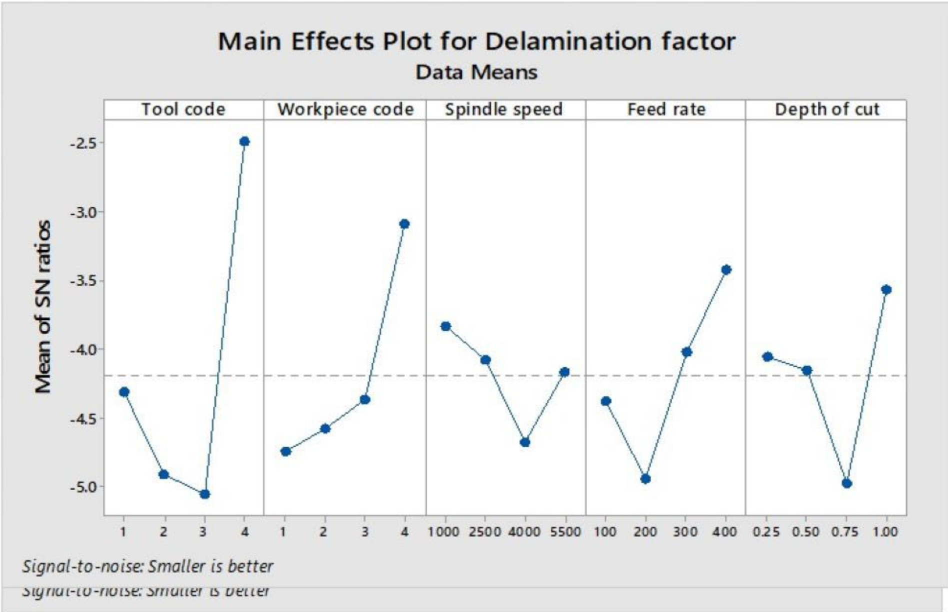


Fig. 3. Mean S/N graph for delamination factor

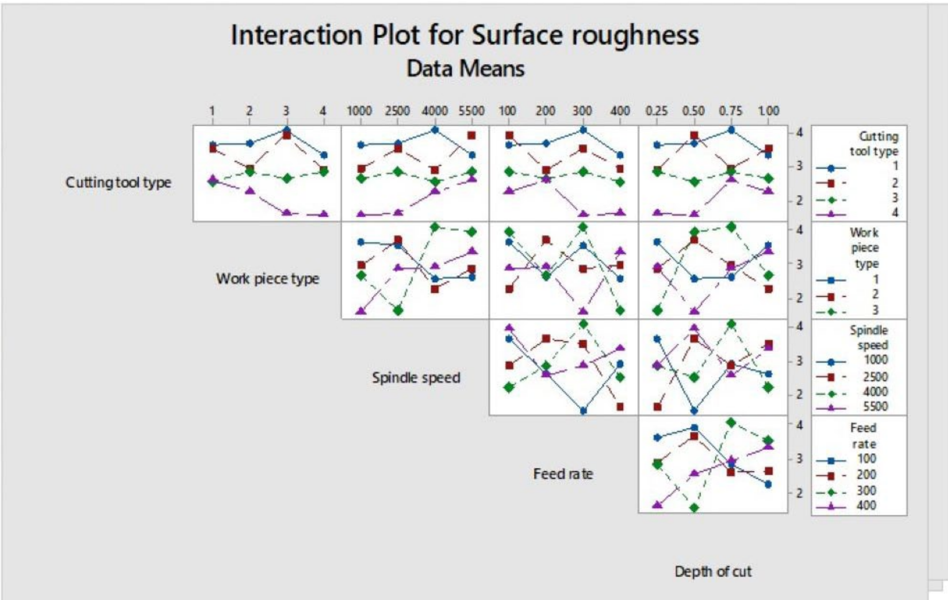


Fig. 4. Interaction plot for Surface roughness using Taguchi L16 OA

4.1.2. SEM analysis

On the other hand, SEM micrographic evaluation is necessary to know the fracture morphology of the milled texture of composites at the micro level. In order to verify the optimal experimental results, a comparative evaluation of statistical analysis with SEM analysis is necessary. Typically, suboptimal tool shape, process variables, workpiece ply angles, and coupled thermal and mechanical qualities affected surface defects. TABLE 3 displays the experiment data, and Figs. 2 and 3 exhibit the main effects of the experiments.

Machining conditions at a feed speed of 300 millimeters per minute, speed of spindle of 1000 revolution per minute and a cutting depth of 0.5 millimeter show a lower surface roughness and a delamination factor of 1.56 µm and 1.1 in PCD milling. Better surface perfection was observed from SEM Fig. 6, when there is little to no negative impact on the milled laminate surface.

Previous studies [19] and [20] indicated that very hard PCD tools are significant in achieving high dimensional accuracy and have longer tool life than carbide tools. In addition, better surface integrity was achieved with a tool with angle of rake and angle of clearance. This study agreed with the above statement and is illustrated below.

The above statement results in the fact that when machining with a PCD tool (36°) with a rake angle, the chip breaking

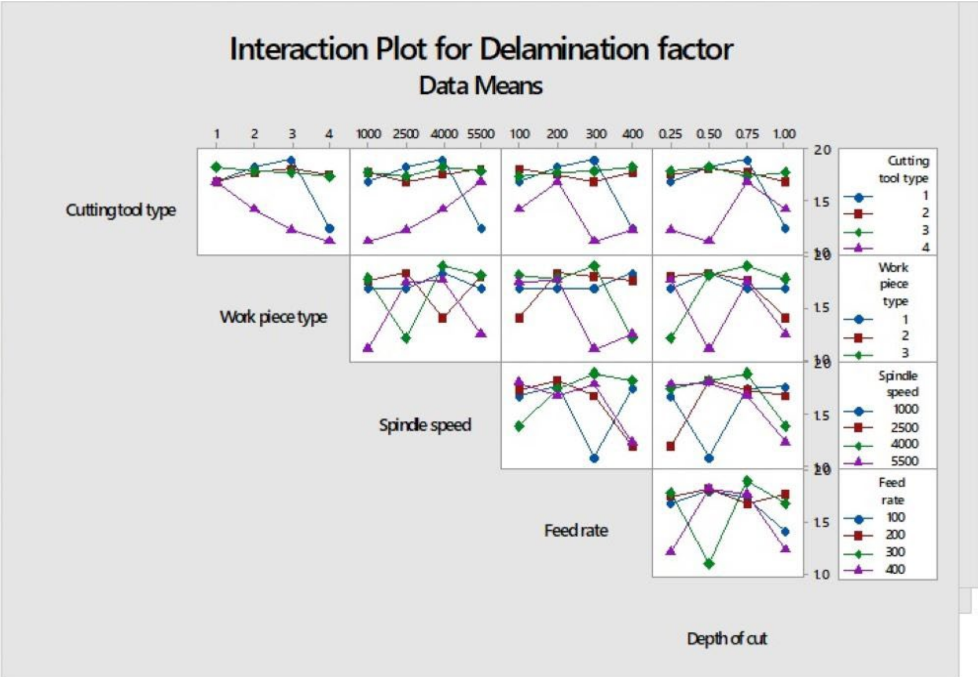


Fig. 5. Interaction plot for dealmination factor using Taguchi L16 OA

length is reduced and the wavy crater damage pattern is greatly reduced, thereby achieving a reasonably better surface finish. The PCD tools' improved angle of clearance (10°) prevents the possibility of a high friction interaction between the tool and workpiece as a result. This prevented the tool from bouncing on the directed length of the fiber and reduced the likelihood of milling force. In addition, the easy pull-out of fibers from the die interface allowed excellent cutting quality. This mechanism measures an indication of lower surface roughness and is shown in SEM Fig. 6.

Furthermore, it was noted in a previous study [10] that the delamination factor decreased significantly with reduced spindle speed and feed rate. The same scenario is shown below. At optimum lower spindle speeds are 1000 rpm, moderate feed is 300 millimeters per minute, and cutting depth is 0.5 mm, providing sufficient plastic deformation expected to smooth fiber cutting and achieve better surface quality. No significant damage was found, which is evident from the SEM Fig. 6.

SEM Fig. 7 shows the micro level of defects eg around the fiber and matrix interface texture (delaminated crack front)

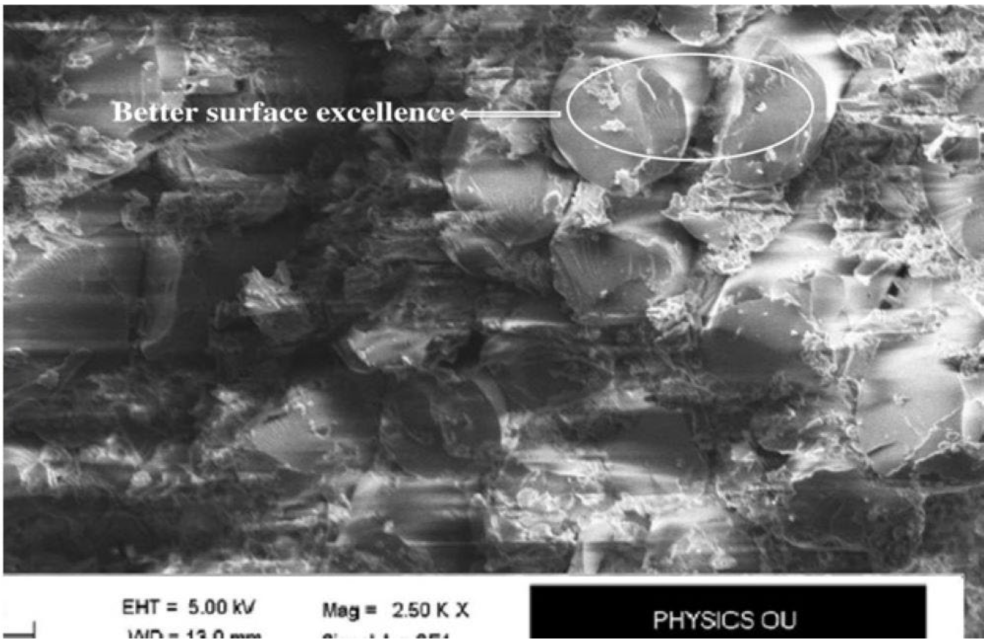


Fig. 6. SEM image of better milled surface of hybrid/epoxy composite with PCD tool at a spindle speed of 1000 rpm, feed rate of 300 mm/min and depth of cut of 0.5 mm

an interlaminar fracture appeared and the fiber bundle pulled out. When machining a carbon/matrix composite laminate with a monolithic carbide tool under milling conditions at a feed speed of 100 millimeters per minute, a higher speed of spindle 5500 revolution per minute and a cutting depth of 0.5 millimeter resulted into a higher surface roughness (3.94 μm). In addition, the solid carbide tool using low rake (30°) and clearance angle (10°) maximized the delamination value by 1.82 accordingly. When milling was done the opposite of the direction of the high-modulus processing grain, the cutting energy across the grain acted in front of the low tool inclination, resulting in chip breaking at the front. This could be due to the possibility of less engagement of the tool face within the turning and workpiece interface. In this case, matrix separation was complicated from the fiber shear zone; as a result, larger chips were produced. The presence of crushed chips is one of the symptoms of a surface defect. This results in the formation of micro cracks in the direction of the fibers, resulting in a degraded surface quality. It could be a delamination failure phenomenon and revealed in SEM Fig. 7.

SEM Fig. 8 represents when machining HSS with a low pitch and clearance tool on a carbon/matrix specimen under machining conditions of (i) feed speed 300 millimeters per minute, (ii) cutting depth 0.75 millimeter, and (iii) speed of spindle 4000 revolution per minute min resulted in a much higher surface roughness and delamination of 4.1 μm and 1.9 respectively. The obtained results could be validated with the following details (i) failures such as crack propagation along the interface and cracking in the matrix occurred. Because at high speeds exceeding

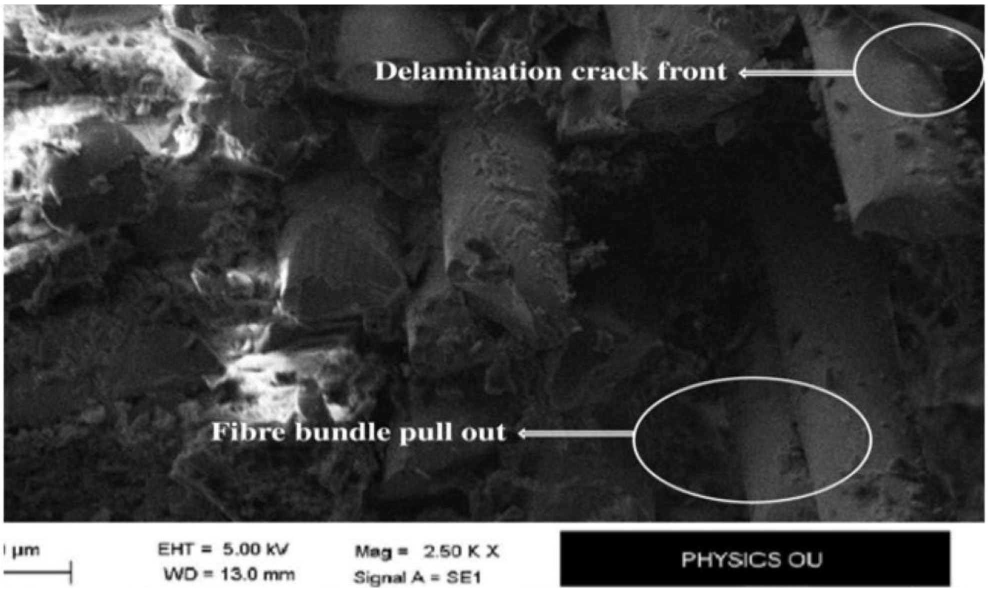


Fig. 7. SEM image of adverse milled surface of carbon/epoxy composite with solid carbide tool at a spindle speed of 5500 rpm, feed rate of 100 mm/min and depth of cut of 0.5 mm

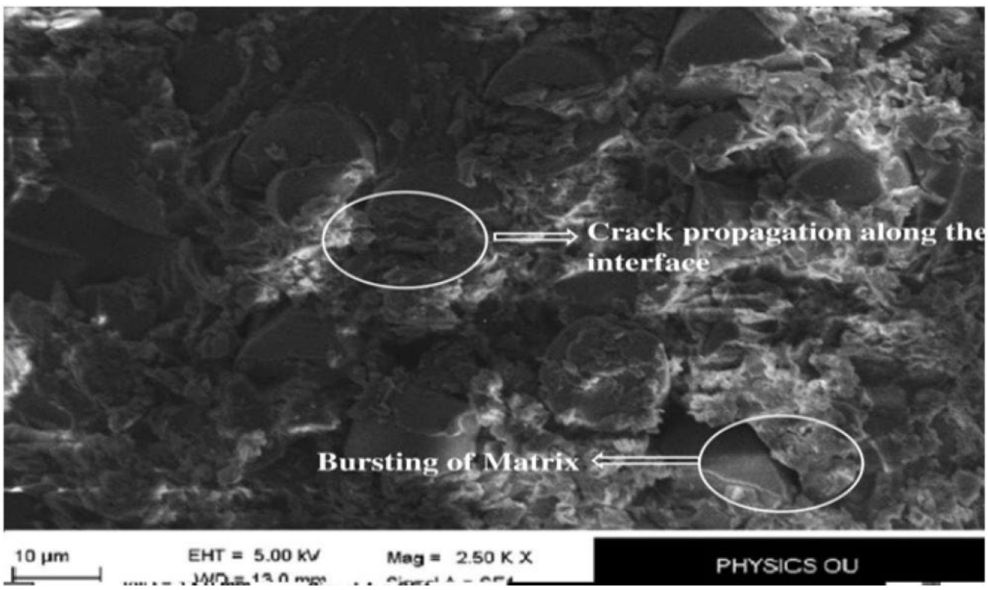


Fig. 8. SEM image of milled surface failures of carbon/epoxy composite with HSS tool at a spindle speed of 4000 rpm, feed rate of 300 mm/min and depth of cut of 0.75 mm

4000 rpm spindle speed. the possibility of induced high temperatures in the machining area. Usually, the epoxy resin softened and weakened, and the molten chips stuck together on the base components and on the cutting tool [21]. Higher spindle speeds generate higher die smearing machining forces and increase surface roughness around the machined texture. Side effects are revealed from SEM Fig. 8. (ii) At a smaller face angle, the possibility of fiber pull-out from the matrix material is typical and excessive torque is required to easily pull the fiber out of the matrix. This created high friction between the tool face and the workpiece. The compressive forces were increased, which in turn caused shear zone friction due to the small tool clearance. From the start of the cut to the end, the size of the shaving chip decreases, creating grooves on the machining zone, this result in the propagation of micro cracks around the fiber-matrix interface [22]. Inter-laminar failure at the fiber-matrix interface can be clearly seen from the SEM Fig. 8.

4.2. Confirmatory tests

Validation tests, however, were carried out to verify the improvement in findings' quality and to determine the significance level between the repeated experimental values (the same ideal set of experimental studies) and the projected values provided by the MINITAB 17 software [23].

The ultimate math model was utilized to estimate the improvement in surface roughness after getting the appropriate coefficients (F-test with a 95% degree of confidence), and the delamination factor is presented below. In TABLE 5, surface roughness and delamination factor values are confirmed by experimental data.

TABLE 5 displays the absolute percentage errors for Ra and F_D in the range of 3-4%, and it was found that the anticipated and experimental values agreed extremely closely.

The percentage improvement of surface roughness and delamination factor is as follows when the design of the experimental values of the ideal setting for the process variables is used and the confirmation findings are taken into consideration:

- Surface roughness improvement in percentage for type-4 tool = [(13, 64, 56)/ 3.64] × 100 = 3.21%;
- Percentage improvement in delamination factor with tool type-4 = [(1.69-1.1)/ 1.69] × 100 = 1.04%.

5. Conclusions

This work was focused on obtaining a possible better surface quality of different FRP composites with different face milling tools. All experiments were performed according to Taguchi's DOE, and the optimal results were also verified by SEM analysis. The comprehensive findings were discussed in Section 4, which led to the following key findings:

1. Identified optimal parametric combinations to achieve attractive surface quality (minimum surface roughness is 1.56 μm and delamination damage is 1.1) having a rate of feed is 300 mm/min, speed of spindle is 1000 rpm, and a cutting depth is 0.5 mm.
2. ANOVA statistical analysis and SEM evaluation show that the PCD tool is highly significant in achieving better surface quality and less damage than the other three tools (HSS tool, solid carbide tool, and customized double fluted carbide tipped tool) on all machined composites laminates.
3. Surface roughness and delamination studies listed that the machined surface quality of hybrid/epoxy composites is much better than the other three types of composite laminates (BD-glass/epoxy composites, UD-glass/epoxy composites, and carbon/epoxy composite).
4. Therefore, irrespective of the process input parameters, the machinable surface's integrity was mostly dependent on tool material and tool angles. From experimental evaluation and SEM micrographic tests, it was found that PCD tool with high angle of rake (36°) and angle of clearance (12°) intended lower machined surface defects than other tools.

TABLE 5

Confirmation experimental results

For surface roughness			
	Starting machining parameters	Optimum machining parameters	
		Prediction	Experiment
Level	A_1 B_1 C_1 D_1E_1	A_4 B_4 C_1 D_3 E_2	A_4 B_4 C_1 D_3 E_2
Surface roughness (Ra) (μm)	3.64	1.5	1.56
S/ N ratio (dB)	–9.21	–10.5	–11.3
Improvement of S/N ratio (dB)	0.8		
Prediction error (dB)	1.126		
For Delamination factor (F_D)			
Level	A_1 B_1 C_1 D_1E_1	A_4 B_4 C_1 D_3 E_2	A_4 B_4 C_1 D_3 E_2
Delamination factor (F_D)	1.69	1.09	1.1
S/ N ratio (dB)	–4.565	–4.924	–5.055
Improvement of S/N ratio (dB)	0.135		
Prediction error (dB)	0.214		

5. This approach can be recommended that continuous improvement in quality and productivity can be expected under optimal parametric conditions with PCD cutting tools over other conventional tools in secondary manufacturing sectors.

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