Experimental investigation of milling operation on GFRP composites

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Abstract. This work attempts to investigate the aspects of machining performance and its optimization during milling operation of glass fibre reinforced composites. Using Taguchi’s design approach, experiments are conducted as per the orthogonal array. The three input parameters considered for the milling operation are the number of flutes, feed rate and cutting speed. The various responses studied during this milling operation are machining force, cutting torque, surface roughness and delamination factor. Also optimization of the machining parameters (ie) number of flutes, feed rate and cutting speed are carried out on milling in order to minimize the surface delamination, machining force, cutting torque and delamination factor. The optimized results obtained after the study are found to be as feed rate of 0.05mm/rev, number of flutes as 4 and cutting speed as 1500 rpm and under these conditions the milling operation performed yielded better surface characteristics.

1. Introduction
Glass Fiber Reinforced Polymer is amongst the most alluring and profitable material among all other designing materials. Its excellent mechanical properties as compared to other conventional metals, increased its utilization especially in aerospace, automotive, defense as well as sports industries. However, machining properties of this composites is somewhat different to the conventional materials as it behaves extremely abrasive during the machining operation due to which various modes of damages like fiber breakage, matrix cracking, fiber–matrix debonding and delamination. Hari et al. [1] studied the edge milling operation on NEMA G-11, GF reinforced composite. The experiment was conducted using L18 orthogonal array and the results have been optimized using grey relational analysis. Four input factors have been considered for experimentation with an output response of three sources. It was found from the analysis, that the milling condition and feed rate were influencing the machining operation. Paneerselvam et al. [2] investigated end milling operation on GFRP composite. The optimization technique adopted for the analysis was grey relational technique. Here four factors were considered as input parameters with an output of four responses.

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The optimized conditions for the milling operation were coated tool, 3 flutes, 79m/min cutting speed and lower feed rate yielded better results. Reddy sreenivasulu [3] investigated end milling operation on GFRP composites using DFA (Desirability Function Analysis). The various parameters considered for the machining operation were S (cutting speed), F (feed rate) and DOC (depth of cut). Ra and DF (delamination factor) were the measured output responses for this experimentation. After measuring the responses, composite desirability analysis was carried out taking into account of both Ra and DF. The optimized values were found to be of lower feed rate and cutting speed with a higher depth of cut yielded improvement in surface characteristics. Durga Prasad et al. [4] studied the end milling operation on GFRP composite using grey relational analysis. The material used for this study was woven fabric and the laminates were prepared using hand layup technique. The machining operation was carried out using solid carbide tool. The input factors considered for the experimental run were S (speed), F (feed rate) and DOC (depth of cut). The measured output responses were Ra and MRR (material removal rate). The outcome of this study was that at lower feed rate and depth of cut, the surface finish was better under the working condition of speed of 4000rpm. Priya and Vinayagam [5] studied the drilling operation on GFRP composites using response surface methodology and grey relational analysis. The authors concluded that the results obtained by both the optimization techniques were found to be the same.

2. Methods

The first step involved in vacuum assisted resin transfer molding is to clean the work table with acetone in order to avoid the dust and remaining from the previous work. After two to three times of cleansing the work area is polished with the wax. Waiting for about 10 minutes wax is removed from the work area. Coatings of PVA resin is applied on the work space. Coating is applied in two layers on a periodic basis with interval of 10 minutes. The glass fiber is placed one above the other in 10 layers. The glass fiber used is biaxial glass cloth of 600gsm density. Sealant tape is applied at a distance of 6 inches from the edges of the work piece in square dimension three times larger than the glass fibers. Placing cello tape in the space between fibers and sealant tape. After placing the tape fix the spiral tube on the cello tape and make sure it does not move. Now place peel ply cloth to cover the glass fiber and green mesh on top of the peal ply only the area covered by the glass fiber. Now with the filament plastic the whole space is covered and pasted it with the sealant tape to make sure no air can enter during the vacuum process. Connecting a pipe with the spiral tube with the help of a T-joint. The end of the pipe is connected to the vacuum machine. After checking that there is no leakage of air the vacuum pump is switched on and let it set for about 1 hour to ensure all the air is sucked out. Mix the resin and the hardener in the ratio of 10:1 in a container. Allow the mixture of resin and hardener to pour over the glass fiber through another pipe and it is distributed throughout the glass fiber. Keep the vacuum pump on for another 4-5 hours the work piece is allowed to dry for more than 24 hours. Make sure the laminates are dry before taking it out. After the laminates is manufactured the edges of the laminates is not linear and hence machining would be not possible if it not straight therefore it needs to be trimmed of the edges. Using the aqua jet cutting machine the samples are trimmed down to a dimension of 100*100 mm. All waterjets follow the same principle of using high pressure water focused into a beam by a nozzle. Most machines accomplish this by first running the water through a high pressure pump. There are two types of pumps used to create this high pressure; an intensifier pump and a direct drive or crankshaft pump. A direct drive pump works much like a car engine, forcing water through high pressure tubing using plungers attached to a crankshaft. An intensifier pump creates pressure by using hydraulic oil to move a piston forcing the water through a tiny hole. The water then travels along the high pressure tubing to the nozzle of the waterjet. In the nozzle, the water is focused into a thin beam by a jewel orifice. This beam of water is ejected from the nozzle, cutting through the material by spraying it with the jet of high-speed water.
In this study, the process is carried out on 3-axis vertical machining centre of model Gaurav-BMV 35 T12, and make BFW whose positioning accuracy is of ±0.005mm, repeatability of ± 0.003mm and with Siemens-Sinumerik 828D Basic CNC controller and the machining process is shown in Figure 1. The tool used in this experiment is end mill cutters whose diameter is of 6mm and three different types of flutes are used here. Number of flutes used is 2, 3, 4. The material of the end mill cutter is HSS (High Speed Steel) as shown in Figure 2.

![Figure 1. Vertical Milling CNC Machine.](image)

Series of experiments have been executed in order to collect response values of machining force, cutting torque, surface roughness (Ra), delamination factor during milling of GFRP. Milling operation has been carried out on GFRP composites for assessing performance characteristics such as load, torque, delamination factor as well as surface roughness of the milled area. Thrust force and torque has been evaluated by using Kistler Milling Tool Dynamometer, whereas, delamination factor has been assessed by using formula given below:

$$F_d = \frac{W_{\text{max}}}{W}$$

where,

$F_d$ = delamination factor,

$W_{\text{max}}$ = maximum width observed in the damaged zone,

$W$ = width of the milling area

![Figure 2. Different End mill cutters.](image)
Machining Performance Characteristics
In order to perform the milling operation, the level of factors and its orthogonal array are shown in Table 1 & 2 respectively. The various input factors are considered for the present study as discussed by [2]. The experimental data for the L9 array is shown in Table 3.

| Machining Parameters | Level 1 | Level 2 | Level 3 |
|----------------------|---------|---------|---------|
| Number of flutes     | 2       | 3       | 4       |
| Cutting speed        | 500     | 1000    | 1500    |
| Feed rate            | 0.05    | 0.10    | 0.15    |

| Sl. No. | Material of the Sample | Number of flutes | Cutting speed (RPM) | Feed rate (mm/rev) |
|---------|------------------------|------------------|---------------------|--------------------|
| 1       | GFRP                   | 2                | 500                 | 0.05               |
| 2       | GFRP                   | 2                | 1000                | 0.10               |
| 3       | GFRP                   | 2                | 1500                | 0.15               |
| 4       | GFRP                   | 3                | 500                 | 0.10               |
| 5       | GFRP                   | 3                | 1000                | 0.15               |
| 6       | GFRP                   | 3                | 1500                | 0.05               |
| 7       | GFRP                   | 4                | 500                 | 0.15               |
| 8       | GFRP                   | 4                | 1000                | 0.05               |
| 9       | GFRP                   | 4                | 1500                | 0.10               |

| Sl. No. | Number of flutes | Cutting speed (RPM) | Feed rate (mm/rev) | Machining Forces (N) | Cutting Torque (kN-mm) | Surface Roughness (µm) | Delamination Factor |
|---------|------------------|---------------------|--------------------|----------------------|------------------------|------------------------|---------------------|
| 1       | 2                | 500                 | 0.05               | 95.38                | 1.505                  | 2.2963                 | 1.297               |
| 2       | 2                | 1000                | 0.10               | 129.1                | 1.396                  | 2.6301                 | 1.275               |
| 3       | 2                | 1500                | 0.15               | 134.2                | 1.45                   | 1.5501                 | 1.43                |
| 4       | 3                | 500                 | 0.10               | 110.01               | 1.916                  | 2.4623                 | 1.13                |
| 5       | 3                | 1000                | 0.15               | 112.6                | 1.461                  | 1.4978                 | 1.386               |
| 6       | 3                | 1500                | 0.05               | 94.19                | 1.71                   | 1.7597                 | 1.22                |
| 7       | 4                | 500                 | 0.15               | 128.2                | 1.06                   | 1.373                  | 1.359               |
| 8       | 4                | 1000                | 0.05               | 103.7                | 1.077                  | 1.887                  | 1.095               |
| 9       | 4                | 1500                | 0.10               | 80                   | 1.011                  | 1.9405                 | 1.198               |

3. Result and Discussion
3.1. Machining Forces and Cutting Torque
In this study, the maximum forces and cutting torque required to mill the GFRP laminates is noted. The parameters are measured using the Kistler mill tool dynamometer and from there we can observe the behaviour along the feed rate using the dynoware software.
Figure 3. Machining force and cutting torque along z axis (2 flutes).
In Figure 3 the graphs depict the changes in the cutting torque and the machining forces along with the time of milling operation. 2 flutes end mill was used at a cutting speed of 500 rpm and feed rate of 0.05 mm/rev to mill and the values for the machining forces is 95.38 N and cutting torque is 1.505 Nm.

Figure 4. Machining force and cutting torque along z axis (2 flutes).
In Figure 4, 2 flutes end mill was used at a cutting speed of 1000 rpm and feed rate of 0.10 mm/rev to mill and the values for the machining forces is 129.1 N and cutting torque is 1.396 Nm.

Figure 5. Machining force and cutting torque along z axis (2 flutes).
In Figure 5, 2 flutes end mill was used at a cutting speed of 1500 rpm and feed rate of 0.15 mm/rev to mill and the values for the machining forces is 134.2 N and cutting torque is 1.450 Nm.

Figure 6. Machining force and cutting torque along z axis (3 flutes).
In Figure 6, the graphs depict the changes in the cutting torque and the machining forces along with the time of milling operation. 3 flutes end mill was used at a cutting speed of 500 rpm and feed rate of 0.10 mm/rev to mill and the values for the machining forces is 110.01 N and cutting torque is 1.916 Nm.
In Figure 7, 3 flutes end mill was used at a cutting speed of 1000 rpm and feed rate of 0.15 mm/rev to mill and the values for the machining forces is 112.6 N and cutting torque is 1.461 N-m.

In Figure 8, 3 flutes end mill was used at a cutting speed of 1500 rpm and feed rate of 0.05 mm/rev to mill and the values for the machining forces is 94.19 N and cutting torque is 1.710 N-m.

In Figure 9, the graphs depict the changes in the cutting torque and the machining forces along with the time of milling operation. 4 flutes end mill was used at a cutting speed of 500 rpm and feed rate of 0.15 mm/rev to mill and the values for the machining forces is 128.2 N and cutting torque is 1.06 N-m.

In Figure 10, 4 flutes end mill was used at a cutting speed of 1000 rpm and feed rate of 0.05 mm/rev to mill and the values for the machining forces is 103.7 N and cutting torque is 1.077 N-m.
In Figure 11, 4 flutes end mill was used at a cutting speed of 1500 rpm and feed rate of 0.10 mm/rev to mill and the values for the machining forces is 80 N and cutting torque is 1.011 N-m.

3.2. Surface Roughness
The Surface Roughness is measured using the surface roughness tester as shown in Figure 12. It has a 2µm diamond stylus.

In Figure 13, the graph depicts the surface roughness of slot 1, which is machined using 2 flute with the cutting speed of 500 rpm and feed rate of 0.05 mm/rev and the value for the average surface roughness is 2.2963 µm.
In Figure 14, the graph depicts the surface roughness of slot 2, which is machined using 2 flute with the cutting speed of 1000 rpm and feed rate of 0.10 mm/rev and the value for the average surface roughness is 2.6301 µm.

In Figure 15, the graph depicts the surface roughness of slot 3, which is machined using 2 flute with the cutting speed of 1500 rpm and feed rate of 0.15 mm/rev and the value for the average surface roughness is 1.5501 µm.

In Figure 16, the graph depicts the surface roughness of slot 4, which is machined using 3 flutes with the cutting speed of 500 rpm and feed rate of 0.10 mm/rev and the value for the average surface roughness is 2.4623 µm.
Figure 17. Surface Roughness for 3 flutes.

In Figure 17, the graph depicts the surface roughness of slot 5, which is machined using 3 flutes with the cutting speed of 1000 rpm and feed rate of 0.15 mm/rev and the value for the average surface roughness is 1.4978 µm.

Figure 18. Surface Roughness for 3 flutes.

In Figure 18, the graph depicts the surface roughness of slot 6, which is machined using 3 flutes with the cutting speed of 1500 rpm and feed rate of 0.05 mm/rev and the value for the average surface roughness is 1.7597 µm.

Figure 19. Surface Roughness for 4 flutes.

In Figure 19, the graph depicts the surface roughness of slot 7, which is machined using 4 flutes with the cutting speed of 500 rpm and feed rate of 0.15 mm/rev and the value for the average surface roughness is 1.3730 µm.
In Figure 20, the graph depicts the surface roughness of slot 8, which is machined using 4 flutes with the cutting speed of 1000 rpm and feed rate of 0.05 mm/rev and the value for the average surface roughness is 1.887 µm.

In Figure 21, the graph depicts the surface roughness of slot 9, which is machined using 4 flutes with the cutting speed of 1500 rpm and feed rate of 0.10 mm/rev and the value for the average surface roughness is 1.9405 µm.

3.3. Delamination Factor
Delamination damage occurs only when machining is done on composites materials. Due to anisotropic nature the laminates tends to distort while the machining is done. Hence the image is captured using Optiv Lite OLM 3020 model as shown in Figure 22. It has a CCD camera which has a resolution capacity of 1/3” attached with VMS 3.1 software and maximum width of the milled area is measured in the laminates as shown in Figure 23a and Figure 23 (b-j) shows the 9 milling slots. To calculate the delamination factor, equation (1) is used.
Figure 22. OLM Machine Vision System.

Figure 23a. Delamination Damage.
Figure 23(b-j). Delamination measurement of the samples.

3.4. Optimization of the Parameters

Taguchi Orthogonal Array Design

L9(3^3)

Factors: 3

Runs: 9

Smaller values are better.

Table 4. Response Table for Signal to Noise Ratios.

| Level | Number of Flutes | Cutting Speed | Feed Rate |
|-------|------------------|---------------|-----------|
| 1     | -35.44           | -34.84        | -33.78    |
| 2     | -34.43           | -35.17        | -34.35    |
| 3     | -34.16           | -34.01        | -35.90    |
| Delta | 1.28             | 1.16          | 2.12      |
| Rank  | 2                | 3             | 1         |

Table 5. Response Table for Means.

| Level | Number of Flutes | Cutting Speed | Feed Rate |
|-------|------------------|---------------|-----------|
| 1     | 31.13            | 29.00         | 25.59     |
| 2     | 27.61            | 29.93         | 27.85     |
| 3     | 26.99            | 26.80         | 32.30     |
| Delta | 4.14             | 3.13          | 6.70      |
| Rank  | 2                | 3             | 1         |

From Table 4 and 5, it indicates the response table for the Taguchi analysis. This is obtained by calculating the average value of each input milling parameters at its corresponding level. The most significant factor affecting the performance characteristics is determined by comparing these value. Based on the results obtained the optimal parameters achieved are number of flutes at level 3, cutting speed at level 3 and feed rate at level 1.
Figure 24. Main Effects plot for S/N ratio.

Figure 24, indicates the most influential parameter as the smallest mean value is the best value obtained by optimization and hence it shows that feed rate is the most influential parameter, then comes number of flutes and then cutting speed. The results obtained through ANOVA analysis for the various responses are tabulated in Table 6-9 and its regression equations are formulated as shown in equations (3) to (6).

Table 6. Results of the analysis of variance for machining forces.

| Source       | DF | Seq SS  | Contribution | Adj SS  | Adj MS | F-Value | P-Value |
|--------------|----|---------|--------------|---------|--------|---------|---------|
| No. of flutes| 2  | 440.7   | 16.38%       | 440.7   | 220.4  | 0.52    | 0.658   |
| Cutting Speed| 2  | 238.3   | 8.85%        | 238.3   | 119.1  | 0.28    | 0.781   |
| Feed Rate   | 2  | 1163.5  | 43.23%       | 1163.5  | 581.7  | 1.37    | 0.422   |
| Error       | 8  | 2691.1  | 100%         | 2691.1  | 423.3  |         |         |
| Total S     | R-sq| R-sq   | PRESS        | R-sq   |        |         |         |
|             | (Adj)| (Adj)  | (Adj)        | (pred) |        |         |         |
|             | 20.5993| 68.46% | 0.00%        | 17185.4| 0.00%  |         |         |

In general, the linear regression equation is given as

$$ X = \beta_0 + \beta_1 Y_1 + \beta_2 Y_2 + \beta_3 Y_3 $$  \hspace{1cm} (2)

Where $\beta_0$ – Constant
$\beta_1, \beta_2, \beta_3$ – coefficient of $Y_1$, $Y_2$ and $Y_3$.

Also, $Y_1$ – No. of flutes
$Y_2$ – Cutting speed
$Y_3$ – Feed rate

The Regression equation for machining forces is
Machining Forces = 114.3 - 7.80 No. of flutes - 0.0084 Cutting speed + 272 Feed Rate  

Table 7. Results of the analysis of variance for Cutting torque.

| Source         | DF | Seq SS  | Contribution | Adj SS  | Adj MS  | F-Value | P-Value |
|----------------|----|---------|--------------|---------|---------|---------|---------|
| No. of flutes  | 2  | 0.63874 | 85.07%       | 0.63874 | 0.31937 | 17.44   | 0.054   |
| Cutting Speed  | 2  | 0.05016 | 6.68%        | 0.05016 | 0.02508 | 1.37    | 0.422   |
| Feed Rate      | 2  | 0.02532 | 3.37%        | 0.02532 | 0.01266 | 0.69    | 0.591   |
| Error          | 2  | 0.03662 | 4.88%        | 0.03662 | 0.01831 |         |         |
| Total          | 8  | 0.75085 | 100%         | 0.75085 |         |         |         |
| S R-sq         |    |         |              |         |         |         |         |
| R-sq (Adj)     |    |         |              |         |         |         |         |
| PRESS          |    |         |              |         |         |         |         |
| R-sq (pred)    |    |         |              |         |         |         |         |
| 0.135320      |    | 95.12%  | 80.49%       | 0.741613| 1.23%   |         |         |

The Regression equation for cutting torque is
Cutting Torque = 2.210 - 0.201 No. of flutes - 0.000103 Cutting speed - 1.07 Feed Rate  

Table 8. Results of the analysis of variance for delamination factor.

| Source         | DF | Seq SS  | Contribution | Adj SS  | Adj MS  | F-Value | P-Value |
|----------------|----|---------|--------------|---------|---------|---------|---------|
| No. of flutes  | 2  | 0.038168| 32.84%       | 0.038168| 0.019084| 2.36    | 0.298   |
| Cutting Speed  | 2  | 0.000979| 0.84%        | 0.000979| 0.000489| 0.06    | 0.06    |
| Feed Rate      | 2  | 0.060893| 52.39%       | 0.060893| 0.030446| 3.76    | 0.21    |
| Error          | 2  | 0.016201| 13.94%       | 0.016201| 0.0081  |         |         |
| Total          | 8  | 0.11624 | 100%         | 2691.1  |         |         |         |
| S R-sq         |    |         |              |         |         |         |         |
| R-sq (Adj)     |    |         |              |         |         |         |         |
| Press          |    |         |              |         |         |         |         |
| R-sq (pred)    |    |         |              |         |         |         |         |
| 0.09000195    |    | 86.06%  | 44.25%       | 0.328064| 0.00%   |         |         |

The Regression equation for delamination factor
Delamination factor = 1.293 - 0.0750 No. of flutes + 0.000021 Cutting speed + 1.877 Feed Rate  

Table 9. Results of the analysis of variance for Surface Roughness.

| Source         | DF | Seq SS  | Contribution | Adj SS  | Adj MS  | F-Value | P-Value |
|----------------|----|---------|--------------|---------|---------|---------|---------|
| No. of flutes  | 2  | 0.27449 | 17.37%       | 0.27449 | 0.137247| 53.0    | 0.019   |
| Cutting Speed  | 2  | 0.15277 | 9.67%        | 0.15277 | 0.076385| 29.5    | 0.033   |
| Feed Rate      | 2  | 1.14747 | 72.63%       | 1.14747 | 0.573734| 221.55  | 0.004   |
| Error          | 2  | 0.00518 | 0.33%        | 0.00518 | 0.002590|         |         |
| Total          | 8  | 1.57991 | 100%         | 1.57991 |         |         |         |
| S R-sq         |    |         |              |         |         |         |         |
| R-sq (Adj)     |    |         |              |         |         |         |         |
| PRESS          |    |         |              |         |         |         |         |
| R-sq (pred)    |    |         |              |         |         |         |         |
| 0.0508887     |    | 99.67%  | 98.69%       | 0.104881| 93.36%  |         |         |

The Regression equation for surface roughness is
Surface roughness = 3.372 - 0.213 No. of flutes - 0.000294 Cutting speed - 5.07 Feed Rate
The Optimization plot obtained from the ANOVA analysis

In Figure 25, it depicts the optimization plot in which it shows that for which parameter the surface roughness and delamination factor are minimal and is having the higher desirability percentage. From this graph the optimal parameter acquired as per there desirability are feed rate as 0.05mm/rev, number of flutes as 4 and finally the cutting speed should be 1500rpm and it is represented in Table 10.

| No. of flutes | Cutting Speed | Feed Rate | Surface Roughness | Delamination Factor | Cutting Torque | Machining Forces |
|---------------|---------------|-----------|-------------------|--------------------|---------------|-----------------|
| 4             | 1500          | 0.05      | 1.82711           | 1.11817            | 1.19978       | 84.0906         |

4. Conclusion
The following points are concluded after the study

- The influence of number of flutes, cutting speed and feed rate on various responses such as Fmax, Tmax, Fd and Ra were analyzed using Taguchi’s design of experiment with L9 orthogonal array.
- The results of the analysis shows that the most influencing parameter is feed rate and then the number of flutes followed by the cutting speed for the milling operation.
- Analysis of variance is carried out and the analytical equations have been developed for the machining force, cutting torque, delamination factor and surface roughness.
• Optimization is carried out and the composite desirability factor is found to be 81% and this is achieved under the operating conditions of higher cutting speed and lower feed rate with the number of flutes as 4 on the milling tool.

• The most contributing parameter is the feed rate for the machining force, delamination and surface roughness because the glass fibres are milled across its cross section and therefore at less feed rate, the Ra, Fd and Fmax are minimum.

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