International Journal of Modern Manufacturing Technologies
ISSN 2067–3604, Vol. XV, No. 3 / 2023
https://doi.org/ 10.54684/ijmmt.2023.15.3.98

CHALLENGES IN MACHINING COMPOSITE MATERIALS: IMPACT OF MACHINING PARAMETERS ON CUTTING FORCE

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Abstract: In the aerospace sector, a hybrid material called CFRP-Aluminum composite is frequently employed. The machining of composite laminate determines the surface integrity and surface polish of the machine part. Excessive cutting forces must be avoided during machining since they are one of the main factors that cause machining problems. By doing this, it is made sure that no waste material is produced during the last phases of production. It is essential to select suitable and perfect machining settings to accomplish the lowest pressure during machining activities. In this study, the issues during the process of CFRP-Aluminum composites milling will be discussed that help utilise various parameters of cutting. A design of experiments method (DOE) was used to run trials with a range of parameter values and levels. Cutting force impacts of machining parameters are assessed by combining Taguchi and statistical analysis of variance (ANOVA). The resulting machining power, which accounts for 54.23 percent for S1 and S2 and 73.57 percent for S2, has the greatest influence on the depth of cut. The feed rate, which accounts for 45.19 percent of the variance in workpiece stiffness and strength, is the factor that has the greatest impact on S3 force. The outcomes proved that there is an adverse correlation exists between cutting forces on one side and feed rate, depth of cut, and cutting speed on the other hand. The results also showed that while the feed rate is set 800 mm/min, the depth of cut is considered 0.2 mm and the spindle speed is set 5000 RPM, the machining force will be minimized.
Keywords: resultant machining force, machining parameters, end milling, Taguchi method, ANOVA.

1. INTRODUCTION

The machining of composite materials is crucial to achieving the requisite geometrical shapes and dimensional tolerances while producing the component for the final assembly. By eliminating materials in the form of chips, traditional machining techniques including are widely employed to develop complicated characteristics in composite parts. The kind and size of chips removed, the velocity at which excess raw material is removed. Sheikh-Ahmad (2009) and Yeganefar (2019) reported that the quality of the surface polish is directly related to the cutting tool and the workpiece.

Fiber reinforced plastic (FRP) products are typically made using the machining technique known as milling. Throughout this process, the elimination of extra material is required to get a well-defined, high-quality surface finish that complies with tolerance criteria (Jahanmir et al., 2000). Fiber that is used in the composite plays a key role and in fact, focusing on the characteristics of it is vital. Moreover, the type of fibre used has a big effect on how machinable FRP is. The fibre used in composite laminates is one of the factors influencing the choice of cutting tools in terms of the cutting edge material and form. Another crucial factor that significantly affects the machinability of composite is the selection of machining settings. (Sheikh-Ahmad, 2009, Jahanmir et al., 2000, Kuntoğlu & Sağlam 2019). The three primary machining variables significantly affect the roughness and smoothness of the surface of a product. Moreover, it can cause a tool to last longer, and consequent machining forces are the speed of the cutting process, the volume of the feeding composite (called feed rate), and depth removing material (or depth cut) (Slamani et al. 2015, Laghari et al. 2020). Understanding the process of cutting a product is crucial and cannot be ignored while optimising the milling process. The ultimate machining force throughout the machining process was a combination of feed forces, thrust forces and cutting forces (Imani et al. 2020). A key technical response parameter for managing the machining process is cutting force, which is defined as the force generated by the cutting device. It is worth knowing that what causes a thrust force is keeping the machining direction and force fixed constant while cutting apart. Feed thrust is used to calculate the power of feed motion. Figure 1 depicts the force elements during the machining process. In addition, the force that resists feed motion is the additional force, sometimes referred to as the feed force. The machining force is produced by the combination of these three elements.

The machining force that results from every cutting situation is shown to have an adverse effect on the speed of cutting. Cutting speed improvements result in a decrease in machining force, which can be considered a positive outcome during machining. (Liu et al., 2010, Safari et al., 2014). The utmost power would rise up and down while the speed of cutting is increased since the impact of temperature decrease and strain hardening on the material. (Huang et al., 2013). As mentioned before, an important factor that had a substantial impact on the final machining force, according to prior studies, is the rate of feeding the composite into a tool. Numerous researchers have reported that during machining, machining force also rises as feed rate does (Ghani et al., 2004, eker et al., 2004, Korkut and Donertas, 2007, Kosaraju et al., 2011, Pathak, 2013). Choosing smoother feed rates (such as 0.1 mm), according to Ghani et al. (2004), is what results in a lower value of the machining force for the specific test range. According to Pathak et al. (2013), when the feed rate rises, chip load per tooth rises as well, increasing cutting force. What impact noticeably in determining the level of required machining force is the cross-sectional area of the not deformed part. This issue was investigated at a 54 percent and 45 percent contribution rate, respectively, in the experiment that was carried out by Azmi et al. (2012). The bulk of prior studies agrees that the aspect that most influences machining force is the depth of cut. As a result, the elements of the cutting force grow as the depth of cut does (Liu et al., 2010, Lacerda and Lima, 2004, Sorrentino and Turchetta, 2011, Sequeira et al., 2012, Jeyakumar et al., 2013, Zenia et al., 2014).

Figure 1 shows the CFRP-Aluminum Laminate design. The current research focuses on the impacts of different machining parameters while using a carbon fibre aluminum composite. For this purpose, a design of experiment method will be used to optimize the machining force.

This method systematically uses Taguchi method and ANOVA to identify the primary impacts of each parameter on the milling process. The best combination of machining settings is anticipated to produce the lowest machining force. To make sure that the predicted optimal parameters match the results of the experiment, a validation test is conducted.

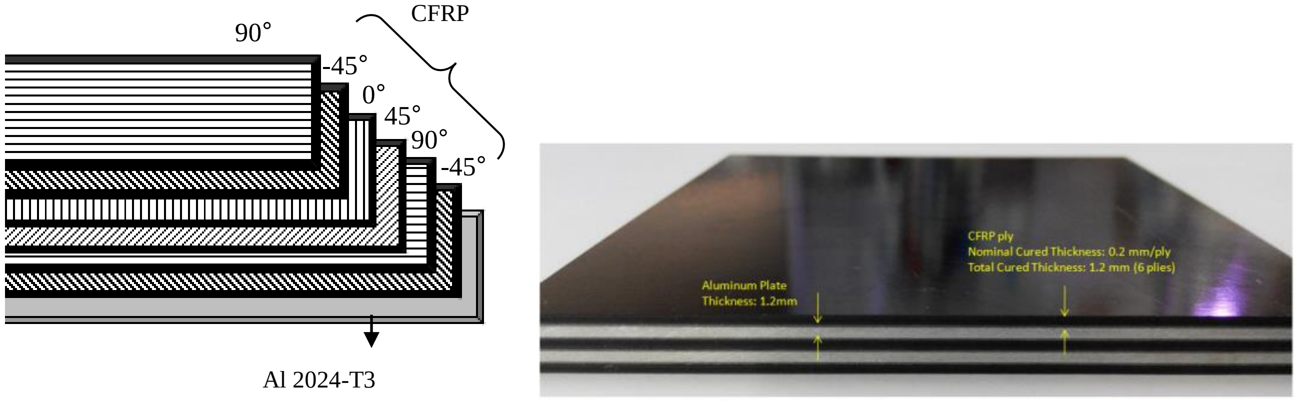

Fig. 1. CFRP-Aluminum Laminate Schematic

2. MATERIAL AND METHOD

The milling process of the CFRP-Aluminum composite laminate is performed in the current study utilising a VF-6 Milling machine. The machining processes are completed in a dry setting. A part with (100 x 100 x 7)mm that is going to be used for milling process has the composition of CFRP and aluminum alloy 2024-T3. In addition, a 6mm diameter polycrystalline diamond is used as the cutting tool for this experiment.

2.1. The Fabrication Process

The workpiece contains layers of UDCF (18) and also aluminum alloy 2024-T3 (2). The epoxy resins, serving as the matrix material, will be applied for manufacture the workpiece. To conduct the experiment, composite laminates were made using an autoclave where the following parameters were set:

- Temp.: 335F;
- Curing Time 120 min;
- Heat/cool process rate: 0.3/0.4 C per min.

The manufactured laminates have a larger volume fraction meanwhile the less number of voids has been observed inside them. Such approach also causes cleaner environment. Complementary sheets of Al 2024-T3 and UDCF prepregs are laminated at 0°, 45°, and 90° angles throughout the manufacturing process. Figure 1 shows the

lamination arrangement of CFRP-Aluminum laminated composites.
The laminates were completed and finalized to the appropriate size, which is 100 mm x 100 mm x 7 mm, after the curing process. Figure 2 shows the three-part experimental setup for the workpiece. These parts stand for area called little, straightforward, and corner.

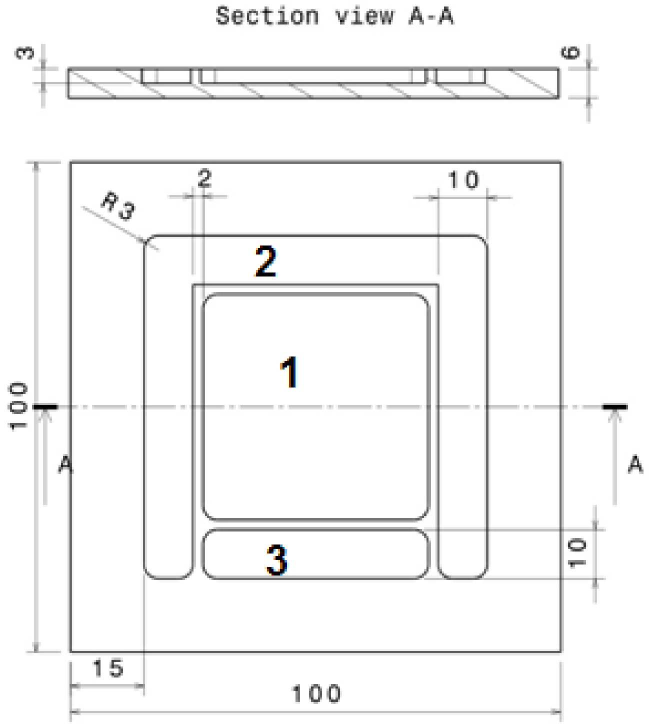

Fig. 2. Sections Must Be Machine

2.2. Milling Process

In order to complete the milling process, a Milling VF-6 machine is used where the levels of essential parameters such as feed rate and speed are given as NC codes. Three portions need to be machined, as seen in Figure 2. Each section has been carefully separated to provide a variety of effects throughout the machining process. In Sections 1, 2, and 3, respectively, the effects of machining on pockets, corner components, and simple parts are shown.
In this study, a polycrystalline diamond (PCD) cutter and computer numerical control (CNC) milling are employed for machining the workpiece. The milling force is also measured using a dynamometer that was installed on the device. Figure 3 depicts the configuration for CFRP cutting process.

Fig. 3. CFRP Machining setup

Fig. 4. Measurement and recording device for machining force data

2.3. Cutting Forces Measurement

Figure 4 depicts the device used to measure force and moment. 9257B Kistler Machining force is measured using a dynamometer. When a dynamometer consisting of quartz crystals is sliced, the force exerted on it creates an electric charge that may be measured in volts, which started about half an hour before the recording data. The amplifier, which is used to support the volts, is checked to make sure it is calibrated before the machine is started. Start synchronising DynoWare and the data acquisition (DAQ) after that, and then modify the DAQ. To change the DAQ, it requires to modify the sample rate, measurement time, and save path location. The process of measuring the data starts, and the data is automatically saved along the selected route. To enable opening in other programs like Matlab or Notepad, the captured data is subsequently converted to a text format.

3. DESIGN OF EXPERIMENTS

The reason for using the design of experiments is twofold. First is to find out which factors are really influential on the response factor, and, second, what are the best settings for each factor. For this purpose, a number of experiments will be designed while different levels of significance are considered for each factor.
This work's experimental matrix was produced utilising the Taguchi method for DOE. The Taguchi methodology is a methodical way to set up an experiment based on an orthogonal array that was meticulously constructed to cut down on the number of tests while still generating highly acceptable findings. The machining force, fm, of the machined surface was affected by three key machining parameters that were employed in this experiment: cutting speed, feed rate, and depth of cut. In addition, for each of the factors 3 levels were considered. These values are in line with the typical parameters for the machining process that were utilised in the industry when PCD cutters are employed. Based on the range suggested by the company that makes the tools, VHF Camfacture AG, the machining conditions are chosen. Each parameter's range needs to be a kind of aluminum and carbon-reinforced plastic since the workpiece is constructed of two distinct materials (CRP). The opted parameters along with the considered levels for each are listed as Table 1.

Table 1. Chosen Machining Levels and Parameters

Factor	Level		
	1	2	3
A- spindle speed (rpm)	3000	4000	5000
B- feed rate (mm/min)	800	1200	1600
C- depth of cut (mm)	0.2	0.3	0.375

All 27 trials for the three components and considered levels of access must be conducted in a traditional complete factorial design. But, by using the Taguchi technique with selected parameters and levels, the current parametric research may be successfully carried out using L9 OA, requiring just nine tests to complete the array.

4. RESULTS AND DISCUSSION

To manufacture a laminate of CFRP-Aluminum with the minimum possible level of pressure during machining, this experiment aims to determine the ideal milling settings to utilise. The outcome is a ratio that will be recorded for each of the experiments:

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} x^2\right) \quad (1)$$

where n depicts the observations and x indicates collected data.
Table 2 displays the real data resulting from the machining force (F_m) of three distinct sections together with the projected S/N ratio (S1, S2, and S3). F_m is calculated using equation 2, where feed force, force during cutting process, and thrust force are shown by Fx, Fy and Fz, respectively.
The variables used in the experimental setup are represented by Equation 2.

$$F_m = \sqrt{{F_x}^2 + {F_y}^2 + {F_z}^2} \quad (2)$$

Table 2. Experimental Results and the Calculated S/N Ratio

RUN	FACTOR			RESULTANT MACHINING FORCE, F_m (N)			CALCULATED S/N RATIO		
	A	B	C	S1	S2	S3	S/N S1	S/N S2	S/N S3
1	1	1	1	14.337	14.510	13.007	-23.129	-23.233	-22.284
2	1	2	2	28.216	23.382	10.574	-29.010	-27.377	-20.485
3	1	3	3	40.385	27.024	16.941	-32.124	-28.635	-24.579
4	2	1	3	26.290	25.595	14.923	-28.396	-28.163	-23.477
5	2	2	1	16.606	14.747	15.297	-24.406	-23.374	-23.692
6	2	3	2	28.973	24.654	21.568	-29.240	-27.838	-26.676
7	3	1	2	18.818	18.230	7.041	-25.491	-25.216	-16.953
8	3	2	3	21.132	18.690	11.175	-26.499	-25.432	-20.965
9	3	3	1	19.483	15.219	15.484	-25.793	-23.648	-23.797

The mean S/N ratio for each level and sector is displayed in Tables 3a, 3b, and 3c, respectively.

Table 3a. Average S/N Ratio Response Table for S1

Factor	Level (S/N)			Max-Min	Rank
	1	2	3		
A	-28.0878	-27.347	-25.928	2.16	3
B	-25.672	-26.638	-29.052	3.38	2
C	-24.443	-27.914	-29.006	4.564	1

Table 3b. Response Table for Average S/N Ratio for S2

Factor	Level (S/N)			Max-Min	Rank
	1	2	3		
A	-22.449	-24.615	-20.572	4.043	2
B	-20.904	-21.714	-25.017	4.113	1
C	-23.258	-21.371	-23.007	1.886	3

Table 3c. Response Table for Average S/N Ratio for S3

Factor	Level (S/N)			Max-Min	Rank
	1	2	3		
A	-26.415	-26.458	-24.765	1.693	2
B	-25.537	-25.395	-26.707	1.312	3
C	-23.418	-26.81	-27.41	3.992	1

Figures 5(a) through 5 illustrate the significant differences between the highest and minimum observed values for S/N ratios of F_m gathered by doing the experiments for spindle speed, feed rate, and depth of cut figure 5(c). Such findings may increase the size of the disparities.

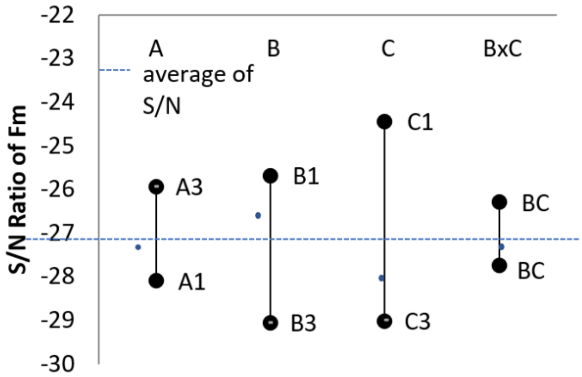

Fig. 5(a). Response Diagram for the Taguchi Method on the S/N Ratio of Cutting Power, F_m for S1

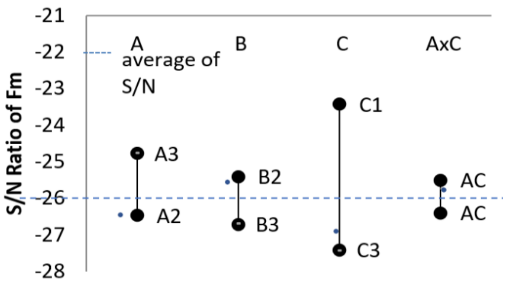

Fig. 5(b). Response Diagram for the Taguchi Method on the S/N Ratio of Cutting Power, F_m for S2

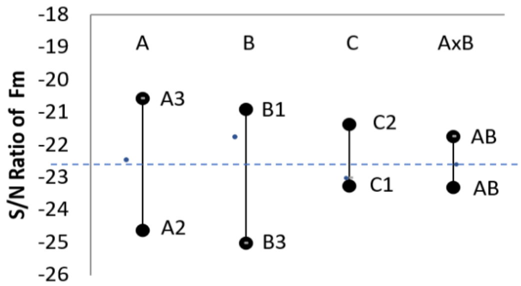

Fig. 5(c). Response Diagram for the Taguchi Method on the S/N Ratio of Cutting Power, F_m for S3

As shown in Figure 6(a), the range of responses is depicted by the graph (c).

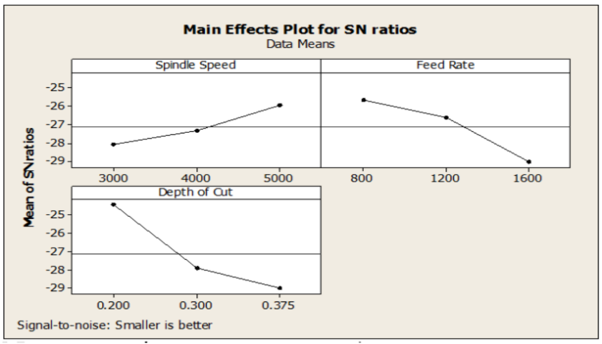

Fig. 6(a). S/N Graph of Resultant Machining Force for S1: Smaller is better

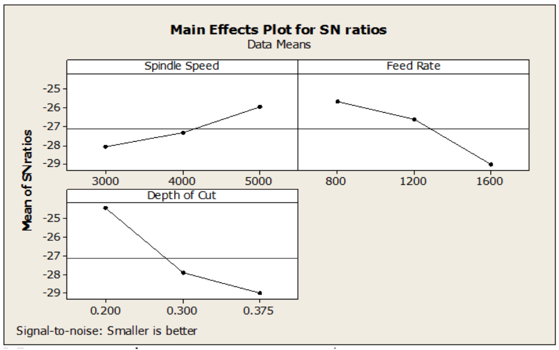

Fig. 6(b). S/N Graph of Resultant Machining Force for S2: Smaller is better

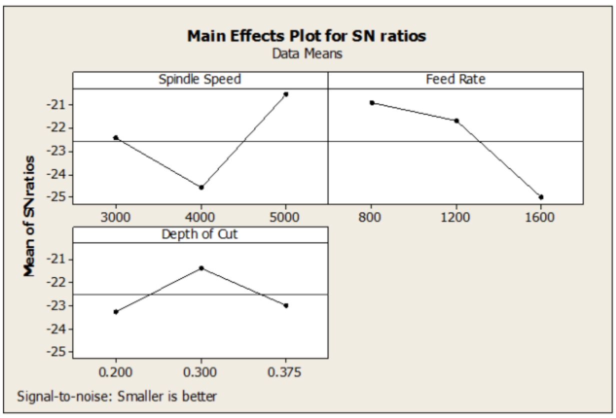

Fig. 6(c). S/N Graph of Resultant Machining Force for S3: Smaller is better

After using Taguchi method for examining the cutting force, the effect of machining settings is investigated on the S/N ratios of machinability output by conducting ANOVA test and also providing the response table. The response table made it easy to easily determine the factors that affect surface roughness by analysing the distance of the greatest and lowest S/N ratio values. The gap increases with the element's impact on cutting force. The results were summarised in Tables 4(a) through 4 in the report (c).

Table 4a. ANOVA Results for S1

Response Factor	Sum of Square	DOF	Mean Square / variance	Ratio (F)	% CTRB
A	7.229	2	3.614	2.162	11.505
B	18.188	2	9.094	5.441	28.947
C	34.071	2	17.036	10.192	54.227
Error	3.343	2	1.671	1.000	5.321
TOTAL	62.831	8			100

Table 4b: ANOVA Results for S2

Response Factor	Sum of Square	DOF	Mean Square / variance	Ratio (F)	% CTR
A	5.591	2	2.795	4.343	14.796
B	3.11	2	1.555	2.416	8.232
C	27.797	2	13.899	21.595	73.566
Error	1.287	2	0.644	1.000	3.407
TOTAL	37.785	8			100

Table 4c: ANOVA Results for S3

Response Factor	Sum of Square	DOF	Mean Square / variance	Ratio (F)	% CTR
A	24.563	2	12.282	6.654	38.967
B	28.485	2	14.243	7.716	45.188
C	6.297	2	3.148	1.706	9.989
Error	3.692	2	1.846	1.000	5.856
TOTAL	63.037	8			100

4.1. Validation Test

A validation test is run to verify the ideal parameter settings recommended by the Taguchi analysis. The tests are carried out under the circumstances of the L9 Taguchi orthogonal array (A3B1C2) and under the conditions of the L9 Taguchi orthogonal array not covered by A3B1C1 (spindle speed = 5000 RPM, feed rate = 800 mm/min, depth of cut = 0.2 mm). Equation 3 from Mohan et al. "Using the optimal level of the design parameters, the predicted S/N ratio may be calculated."

$$\hat{\eta} = \eta_m + \sum_{i=1}^{q} \tilde{\eta} - \eta_m \quad (3)$$

where:

$\hat{\eta}$ = Estimated S/N ratio;
η_m = Total mean at the S/N ratio;
$\tilde{\eta}$ = Mean of S/N ratio at optimal level;
q = Number of the experimental parameters used in Taguchi L9 experiments

Table 5 indicates results of conducting the experiments to validate the designed process where the corresponding S/N ratio for each experiment is calculated and reported. The average experimental results and their accompanying S/N ratios are calculated using the specified parameter values. The predicted outputs at the desired values of A3B1C2 and A3B1C1 are shown in Tables 6 and 7, respectively.

Table 5. Results of validation experiments

	Experimental Results ($A_3B_1C_2$)			S/N Ratio ($A_3B_1C_2$)		
Sections	S1	S2	S3	S1	S2	S3
Force (N)	16.257	31.643	16.019	-24.221	-30.006	-24.093
	Experimental Results ($A_3B_1C_1$)			S/N Ratio ($A_3B_1C_1$)		
Sections	S1	S2	S3	S1	S2	S3
Force (N)	13.366	16.078	14.326	-22.520	-24.125	-23.123

When comparing experimental and predicted results, only S1 is taken into account, as the data from the other machined portions have a consistent pattern. The experimental values of the ideal parameter setting are pretty close to the conclusions of the calculations for the machining force, F_m, as can be seen in Tables 6 and 7. The A3B1C1 sequence generates a greater final machining force based on both findings.

Table 6. Experimental and predicted results comparison in a desirable setting (A3B1C2)

	Resultant Force, F_m	
Average of S/N, η_m	-25.88	
Level	Ave. Exp	S/N
3	19.811	-25.928
1	19.815	-25.672
2	25.335	-27.914
Desirable Value, $\tilde{\eta}$	Calculated S/N	-25.272
	Experimental S/N	-24.221
	% Error	4.34%

Table 7. Experimental and Predicted Results Comparison in a Desirable Setting (A3B1C1)

	Resultant Force, F_m	
Average of S/N, η_m	-27.121	
Level	Ave. Exp	S/N
3	19.811	-25.928
1	19.815	-25.672
1	16.809	-24.443
Desirable Value, $\tilde{\eta}$	Calculated S/N	-21.801
	Experimental S/N	-22.52
	% Error	3.20 %

According to the validation tests, using Taguchi DOE to assess machining parameters can be a more effective and trustworthy way to look at how the factors affect the output of machinability. The Taguchi technique, therefore, permits the choice of the ideal parameter settings to minimise or optimise the machinability output when end milling CFRP-Aluminum composite laminates.

4. CONCLUSION

The final machining force is influenced by a unique main parameter, F_m, for each piece that is machined. Depth of cut is thought to have had the most impact on the F_m for S1 and S2, contributing 54.23 percent for S1 and 73.56 percent for S2. However, for S3, feed rate, which contributes 45.19 percent, is found to be the most significant factor that affects F_m. The rate of feeding the material and cut length are the factors that significantly impact the F_m because they influence the cross-sectional width of a sheared part. The affected factor for S3 is different since the workpiece's strength and stiffness were altered after the S1 and S2 were machined.

To reduce the resultant machining force, the appropriate machining settings are selected. Inverse relationships exist between the resulting force and the feed rate, depth of cut, and spindle speed. Generally speaking, less machining force is required when employing a rapid spindle speed, a medium feed rate, and a shallow cut. Set the feed rate to 800 mm/min, the spindle speed to 5000 RPM, and the cut depth to 0.2 mm.

5. ACKNOWLEDGEMENT

The Ministry of Education Malaysia (MOE) for my PhD scholarship and the Ministry of Science, Technology, and Innovation Malaysia (MOSTI) through the eSciencefund grant (5450737) are both acknowledged by the authors.

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Received: April 26, 2023 / Accepted: December 15, 2023 / Paper available online: December 20, 2023 © International Journal of Modern Manufacturing Technologies