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https://doi.org/10.5109/6792826

出版情報：Evergreen. 10 (2), pp.765-773, 2023-06. 九州大学グリーンテクノロジー研究教育センター
バージョン：

Optimisation of Machining Parameters for CNC Milling of Fibre Reinforced Polymers

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(Received December 25, 2022; Revised April 26, 2023; accepted May 14, 2023).

Abstract: The objective of the presented work is to improve the machining parameters of fibre reinforced polymer (FRP) using Taguchi's robust design technique. A large number of variables impact the quality of the completed component throughout the machining process. The quality of machined FRP components is greatly influenced by the surface roughness. Manufacturers can make sure that the finished product fulfils the necessary quality requirements and is cost-effective by optimizing machining settings to achieve the specified surface roughness. Optimizing machining parameters for achieving the desired surface roughness can help reduce production costs by minimizing waste, improving tool life, and reducing the need for post-processing operations. To optimize the process, Three levels of each parameter were chosen for investigation for each such adjustable process parameter. Machining was performed on a CNC milling machine using a carbide end mill. Experiments were conducted utilising Taguchi's technique to generate an experiment design (L9 orthogonal array). Analysis of variance was used to determine the impact of each parameter (ANOVA). The recommended control factor values for the best possible surface finish of FRP are 1.64 m, 400 rpm spindle/cutting velocity, 1.5 mm depth of cut and 0.3 millimetre/revolution feed rate. Surface roughness was shown to be most impacted by cutting speed, followed by feed rate and depth of cut. To determine the relationship between process parameters and quality attributes, regression analysis and response surface methodology was used.

Keywords: Fibre reinforced polymers (FRP); machining parameters; Taguchi; surface roughness; optimization

1. Introduction

Fibre-reinforced polymers (FRP) have wide applications in the current economy due to good corrosion resistance, lightweight, good dielectric strength, high fracture toughness, low moisture absorption, thermal resistance and high specific stiffness therefore they have wide application in the aerospace industry, automobile industry, lightweight furniture and electrical insulators[1]. FRPs are also gaining popularity due to their superior mechanical qualities and affordable cost[2,3]. Recently, FRP has replaced stainless steel and other comparable materials because it has advantages such as a high strength-to-weight ratio, stiffness-to-weight ratio, excellent damping, and low heat[4]. Although with wide applications but FRP users face a number of machining challenges, this is due to the fact that the technical basis developed for conventional materials cannot be used for such new materials since their ability to process differs from standard materials. Some issues connected with FRP machining include material heterogeneity, delamination damage, and surface roughness[5]. Because surface roughness has such a big influence on dimensional precision and material performance, a lot of effort has been put into developing models that employ experimental design to estimate surface roughness and quantify machined surfaces[6]. Surface roughness affects mechanical characteristics including fatigue, corrosion resistance, and creep, as well as functional aspects including light reflection, friction, electrical conductivity, wear, heat transfer and lubrication[7]. Various machining operations are used in the manufacturing business to remove material from FRP to generate a better product based on their capacity to remove undesirable material while preserving a good surface quality. End milling is one of the most widely used, simple and easy metal cutting techniques used for machining of components and parts frequently. Complicated shapes/forms can be machined with a high surface finish during milling operations[8-10]. CNC machine tools have been utilised to automate milling in recent years because they increase; output while requiring very less intervention from the operator side. As the demand for flexibility and agility has increased, new CNC machines have grown more stable and robust, making determining the right amounts of cutting parameters during CNC milling operations more difficult[11]).

Several machining parameters make up the machining process. For low (surface roughness of the surface, wear of tool, cutting force, temperature, and so on) or high (material removal rate) machining responses, the optimization technique offers a preferable parameter combination[12]). The most critical cutting parameters for end milling machining were cutting speed, depth of cut, and feed rate[13,14]). As a result of improper parameter selection, cutting tools wear down quickly, resulting in economic losses such as destroyed work-piece(s) and bad surface quality[15]). For a specific application, achieving appropriate surface roughness during machining (milling) is required, which is influenced by different cutting parameters and tool geometry[16]). The quality of machined FRP components is greatly influenced by the surface roughness. Manufacturers can make sure that the finished product fulfils the necessary quality requirements and is cost-effective by optimizing machining settings to achieve the specified surface roughness. Optimizing machining parameters for achieving the desired surface roughness can help reduce production costs by minimizing waste, improving tool life, and reducing the need for post-processing operations. Optimization techniques such as the Taguchi method and response surface methodology (RSM) have been used to optimize machining parameters for improving surface roughness in FRP composites. The Taguchi method is a statistical design of experiments technique that determines the optimal combination of machining parameters based on the signal-to-noise ratio. RSM is a statistical method that models the relationship between the machining parameters and surface roughness. Regression analysis is computational models that learn from historical data to predict surface roughness based on machining parameters[17,18]).

In present study all major machining parameters like cutting speed, feed rate and depth of cut are taken into consideration. Based on the components and levels that were explored can be achieved by the various design of experiments techniques (DOE)[19]). In the present study, the DOE was built using Taguchi's L9 orthogonal array[20]). Taguchi's S/N ratio analysis and preference approach are used to reduce surface finish and optimise cutting variables during milling. Surface roughness was monitored with the objective that smaller is better and the influence of each parameter was carried out using analysis of variance (ANOVA). Finally, we conduct confirmation tests to compare the experimental and calculated results.

2. Materials & methods

The experiment was carried out on a CNC machine, which requires mounting and fastening the workpiece on the CNC machine bed to avoid vibrations and deflections during the milling process. The CNC machine (JYOTI PX40 VMC) utilised in this investigation has the parameters provided in Table 1 and represented in Fig.1.

Table 1. CNC milling machine specifications

Type of machine	Vertical machine centre
Machine	JYOTI PX 40 VMC PX Series
Table size	915 x 460 mm
Spindle motor capacity	8.25 kW
Spindle speed (max)	6000 rpm
Feed rapid traverse (X, Y & Z Axis)	25 m/min
Feed cutting	10 m/min
Accuracy (positioning)	0.01 mm
Accuracy (repeatability)	0.005 mm

Fig.1: Machining of FRP on CNC milling

2.1 Work-piece and Tool

Tool with high hardness like solid carbide end mill of 40 mm flute length and 6 mm diameter is selected for machining as it has better thermal conductivity and modulus of elasticity in comparison with most available other tool materials. Selected tool also helps to achieve better surface finish with a high level of dimensional accuracy.

FRP (fibre reinforced polymer) used in this study is a sample of sheet used in construction sites which typically consist of a polymer matrix that has been reinforced with glass fibres. The polymer matrix is typically an epoxy resin, the glass fibers used in FRP sheets for construction sites are typically made from E-glass, In addition to the polymer matrix and glass fibers, FRP sheets for construction sites may also contain fillers or additives such as calcium carbonate or silica. Test specimen of FRP having length of 400 mm, width 300 mm and thickness of 5 mm. Specimen sheet used in this study is directly purchased from the market-place. Typically, E-glass, a form of fibre-glass with exceptional fatigue, impact, and chemical resistance, is used to make the glass fibres in FRP sheets for building sites. E-glass has a high modulus of elasticity, strong tensile strength, compressive strength, and flexural strength. The FRP sheet's strength and stiffness are provided by the fibres, which are normally woven or stitched into a precise pattern.

2.2 Design of experiments (DOE)

Traditional experimental design methodologies are inherently complex and difficult to execute; however, Novel orthogonal array design using the principle of Taguchi methodology was used to overcome this issue to optimize the parameters with limited experiments[21)]. It is a set of experiments aimed to collect data in a controlled setting to learn more about process behaviour. The Taguchi robust design approach is used because it is a useful tool for quickly finding key parts, producing a high-quality system, and cutting down on experimental/cutting time[22)]. The orthogonal array helps in reducing the amount of experimental work by using design criteria with controlled factors in the columns and standard level of quantities in the row. Taguchi suggested the use of the efficacy metric signal to noise ratio (S/N)[23)]. The (Taguchi) optimization process flow diagram used in this study is depicted in Fig. 2.

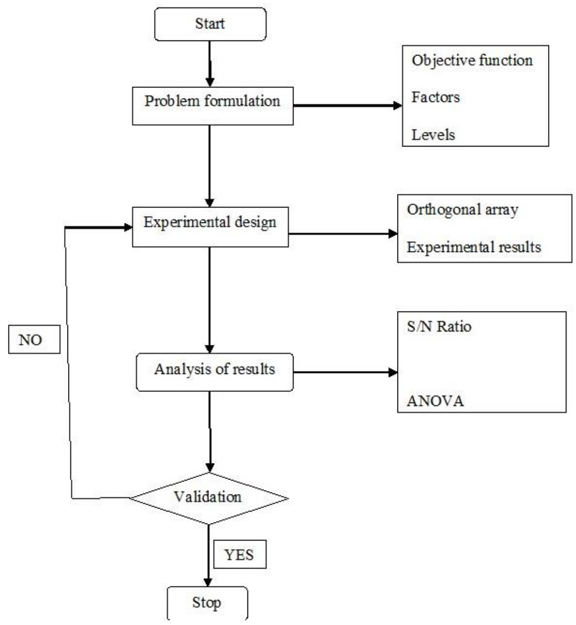

Fig.2: Process flow diagram for optimization technique

2.3 Implementation of the Taguchi

This approach comprises creating an experiment to do research in a controlled way, followed by testing to learn more about the behaviour of a certain process. This research aimed to determine how different machining settings influenced FRP composite milling. Statistical experiments based upon Taguchi techniques were used to calculate surface-roughness under the influence of various machining parameters. Several research on milling process parameter optimization have been undertaken, each focusing on a distinct approach and set of parameters. There are some outstanding instances of published research that used the Taguchi technique for parameter optimization. During milling with the maximum speed of 200 rpm, the depth of cut is 1.25 mm, and feed is 0.48 millimetre/revolution[16)], 200 – 550 rpm, 0.6 – 1.8 mm depth of cut[16)]. Overall, the selection of input parameters and levels for machining requires careful consideration. Here input parameters speed, feed and depth of cut are most relevant and are selected on the basis of early studies and taking into consideration the machine and tool range of available CNC (JYOTI PX40 VMC) as well as objective to minimize the surface roughness. Table 2 displays the many aspects and their levels that were properly selected for the investigation.

Table 2. Machining parameters and their levels

S.No.	Factor	Levels		
		1	2	3
1	Speed (rpm): N	300	400	500
2	Depth of cut (mm): D	1	1.5	1.75
3	Feed (millimetre/revolution): F	0.3	0.45	0.6

3. Experimental setup

Table 3 shows the experiment plan, which considers three different factors at three different levels, resulting in the selection of the L9 orthogonal array (OA) with nine experiments[24)]. The above-mentioned OA completed all nine runs (slots) (L9). Three input/control parameters, used in this study: The factors and their values were chosen based on a survey of the literature, and the reason for their selection and levels is explained below.

(a) Speed: The rate at which the spindle and work piece move is measured in RPM in this experiment for optimization reasons.

(b) Feed rate: It is the pace of the cutting tool progressing along its cutting path. The feed rate is given in millimeters per rotation.

(c) Depth of cut: The distance between the work piece's uncut and cut surfaces, measured in millimeters,

As a response variable, surface roughness (Ra) was used. The goal was to keep the surface area to a bare minimum. Surface roughness is defined as the average difference in surface height compared to the reference plane.

Table 3. Selection of L9 orthogonal array

Experiment number	Control factor		
	N (rpm)	D (mm)	F (millimetre/revolution)
1	300	1.00	0.30
2	300	1.50	0.45
3	300	1.75	0.60
4	400	1.00	0.45
5	400	1.50	0.60
6	400	1.75	0.30
7	500	1.00	0.60
8	500	1.50	0.30
9	500	1.75	0.45

3.1 Measurements

Surface roughness is one of the metrics used to assess the mach-inability of a work piece and is also a significant consideration to find whether the surface is suitable for a specific function as rough surfaces are normally more vulnerable to corrosion and crack but it aids in adhesion[25]. The surface roughness of the machined surfaces was measured using a Mitutoyo SJ-201: surface roughness tester, which has a measuring range of -200 μm to +150 μm. (Fig.3). Each experiment was repeated thrice to check the accuracy of the reading collected. The roughness: tester displays the mean roughness: value and the measured roughness depths (Rz) in micrometers or microns (Ra).

Fig.3: Machined (slotted) work-piece three samples for each experiment

4. Results and Discussions

Table 4 represents the results of experiments conducted in this study and summarizes the values of data of surface roughness as well as its S/N ratio for various factors at each level the purpose of each experiment was used to find the best possible S/N ratio[26]. As a result, the mean squared deviation should be as low as possible, indicating a minimal divergence from the desired feature's threshold. In an experiment, maximizing the S/N ratio is critical[27]. The higher the signal-to-noise ratio, the more valuable the intended signal is. Table 3 shows the experimental parameter combinations. In the present study experiment was conducted with three repetitions for each combination of input parameters therefore 27 slots are cut as shown in fig. 3. This specific repetition will help to improve the variability in the data of surface roughness (output parameter) with desired level of precision.

Table 4. Result of surface roughness (μm)

Experiment	1st	2nd	3rd	Average	S/N
1	2.62	2.38	2.67	2.556	-8.15122
2	2.67	1.71	1.54	1.973	-5.90254
3	2.63	1.74	2.85	2.406	-7.62591
4	2.67	2.27	2.11	2.350	-7.42136
5	1.33	1.77	1.83	1.643	-4.31275
6	1.54	2.09	1.91	1.846	-5.32463
7	2.08	2.83	1.87	2.260	-7.08217
8	2.05	2.40	2.89	2.446	-7.76913
9	2.28	1.79	2.31	2.126	-6.55127
Average				2.178	-6.68233

Table 4 summarizes the experimental findings for surface roughness and their S/N ratios for the nine (9) trial situations. At a cutting velocity of 400 rpm, a depth of cut of 1.50 mm, and a feed rate of 0.60 millimeter/revolution, a minimum surface roughness (R_a) of 1.643 m was attained in experiment 5. In general, a higher surface quality was achieved by combining a moderate cutting velocity, moderate depth of cut, and the highest feed rate. The largest surface roughness (R_a) of 2.556 μm was obtained with trial 1, at the lowest cutting velocity (300 rpm), depth of cut (1 mm) and feed rate (0.3 millimeter/revolution).

The lines connecting the quantities of components in Fig. (4-5) are not horizontal, implying that each parameter has a varied influence. The lowest and highest values of the S/N ratio are recorded at speed level 2 (400 rpm), depth level 2 (1.50 mm), and feed level 1 (0.3 millimeter/revolution). These control factor amounts are optimal for reducing surface roughness. Fig.4 shows that when cutting velocity (A) increases from level 1 to level 3, surface roughness reduces from 2.32 to 1.95 m and then increases to 2.29 m. Surface roughness was found to decrease from 2.38 to 2.0 μm and further increase from 2.0 to 2.12 μm as the depth of cut (B) increases from level

1 to level 3. Surface roughness increased; from 2.0 to 2.4 m as the feed (C) was increased from 0.3 to 0.6 millimeter/revolution, because at higher depths of cut, a larger area: of the tool is in contact with the FRP, resulting in increased load on the tool and higher frequency vibration, resulting in increased surface roughness; surface roughness also increased from 2.0 to 2.4 m as the feed (C) was increased from 0.3 to 0.6 millimeter/revolution. On the major impacts plot of the S/N ratio, Fig.5, the best combination of surface roughness factor parameters is A2B2C1 which matches the maximum values of S/N ratios and the smallest means for all the control parameters.

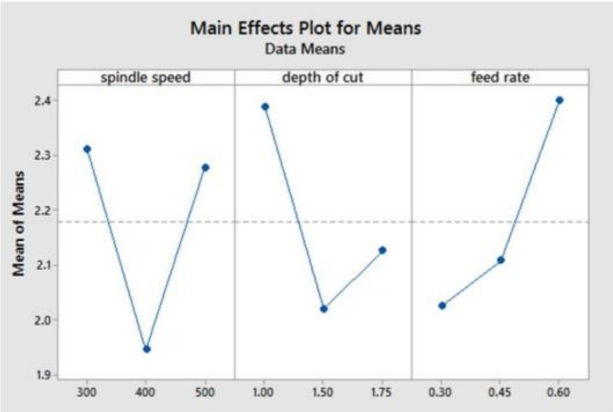

Fig.4: Main effects plot for means

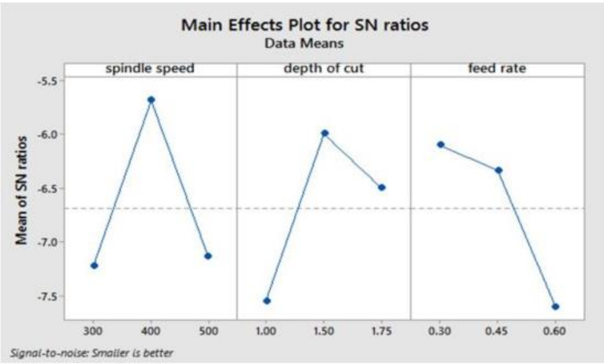

Fig.5: Main effects plot for S/N ratio

4.1 ANOVA

In order to determine how input factors: affect output variables, an analysis of variance (ANOVA) is used[28]. The ANOVA values for the output factors that were assessed are displayed in Table 5 as well. In this study, the aggregates of squares and variations are determined, and an F-test: is used to choose the essential components with a 95% confidence level. When surface roughness was taken into account, cutting (spindle) speed (32.81%) was the main parameter of concern, followed; by parameters feed rate (31.22%) and depth of cut (28.96%).

$$\%\text{contribution} = \frac{\text{sum of squares (Adj SS) of each factor}}{\text{Total number of sum of squares}}$$

Table 5. ANOVA for surface roughness

Source	DOF	Adj. SS	Adj. MS	P-value	% Contribution
Spindle speed	2	0.024421	0.012210	0.017	32.81
Depth of cut	2	0.021551	0.010776	0.019	28.96
Feed rate	2	0.023231	0.011615	0.018	31.22
Error	2	0.005215	0.002607	-	7.01
Total	8	0.074418	-	-	

4.2 Confirmation experiment

The major goal of this study's confirmation test is to find the best process parameter (A2B2C1) for the machined surfaces. The anticipated mean (μ) is the expected value of the average result produced by the experimental data. The parameter range must be specified at a specific level of confidence, and the average value must be within a particular percentage of confidence[29,30]. Table 6 shows the outcomes of three trials performed with the best machining settings combination.

Table 6. Results of confirmation experiment

Machining parameter	Level	Surface roughness, R_a (μm)			
		Experiment 1	Experiment 2	Experiment 3	Average
Cutting velocity (rpm)	400	1.65	1.70	1.57	1.64
Depth of cut (mm)	1.5				
Feed (millimetre/revolution)	0.3				

The predicted confidence interval (95% confidence level) was found to lie within the confidence interval validating the experimental results $1.37 < \mu SR < 1.66$. The anticipated best value is 1.57 µm, but the actual (average) value is 1.64 µm. The confirmatory experiment's results were found to be within the confidence interval, suggesting that the experimental result was legitimate.

4.3 Validation of the model through experiments

A first-order regression model was utilized to analyse the change in surface roughness (Ra) with different machining settings[31,32]. The MINITAB – 20 software and the experimental data were used to construct the regression coefficient. The multiple linear regression equation for surface roughness (Ra) may be represented in real factor form:

$$R_a = 3.091 - 0.00017*\text{cutting speed} - 0.405*\text{depth of cut} - 0.599*\text{feed rate}$$

Table 7 compares measured and projected R_a. The exact deviation and expected value are represented by the deviation sequence (Δ). It is clear that most of the Ra values predicted by the first-order regressive model are near the experimental values; the average error is 1.03 per cent, which is comparable to reported values when compared to published research work; hence, this model may be employed for future examination.

Table 7. Comparison between measured and predicted results of R_a

Experiment	Measured R_a (µm)	Predicted R_a (µm)	Deviation for R_a (Δ)	% Error
1	2.556	2.455	0.101	3.95
2	1.973	2.162	0.189	-9.58
3	2.406	1.972	0.434	18.03
4	2.350	2.348	0.002	0.085
5	1.643	2.056	0.413	-25.13
6	1.846	2.134	0.288	-11.37
7	2.260	2.242	0.018	0.796
8	2.446	2.219	0.227	9.28
9	2.126	2.028	0.098	4.61
Average error			0.197	-1.03%

As previously said, little research was done on the creation of a regression model for RSM-based performance predictions[33]. RSM is a powerful statistical tool for optimizing machining parameters to improve surface roughness in FRP composites. Several optimal solutions exist for many engineering optimization problems, one or more of which may be the absolute minimum or maximum. Response surface plots are used in statics to investigate the correlations between many explanatory and one or more response variables[34,35]. Because the model contains three variables, one of them can be held constant at the plot's centre level, resulting in three response surface plots. The interaction influence of cutting velocity and depth of cut is demonstrated in Fig. 6. The virtually circular part of the curve indicates that at a medium cutting velocity and medium depth of cut, the surface roughness value is much less than 1.8 µm, and it performs better than any other combination of cutting velocity and depth of cut. As a result, the milling operation should be done at a 1.5 mm depth of cut with a 400-rpm cutting velocity to achieve the lowest possible surface roughness. The dark green shaded zone indicates the possibility of low surface roughness at a medium cutting velocity and depth of cut.

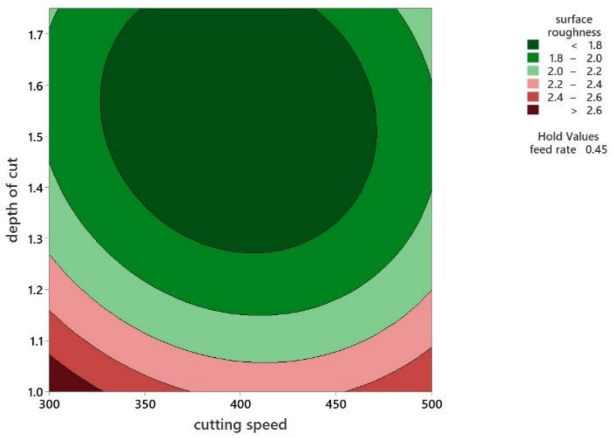

Fig.6: Contour plot showing the effect of cutting speed (rpm) on the depth of cut (mm) on surface roughness (feed rate 0.45 millimetre/revolution)

At a constant depth of cut of 1.375 mm, Fig. 7 shows the effects of feed rate: and cutting speed on surface roughness. The graph shows that a lower cutting speed and feed rate will produce the minimum amount of surface roughness: compared to other cutting velocity and feed rate combinations, with a surface roughness value that is lower and is obtained in the range of 1.8 to 2 µm. The dark green shaded area indicates the possibility of minimum surface roughness at an optimum range of cutting velocity of (300 - 400) rpm and at a lower feed rate of (0.3 - 0.45) millimeter/rev.

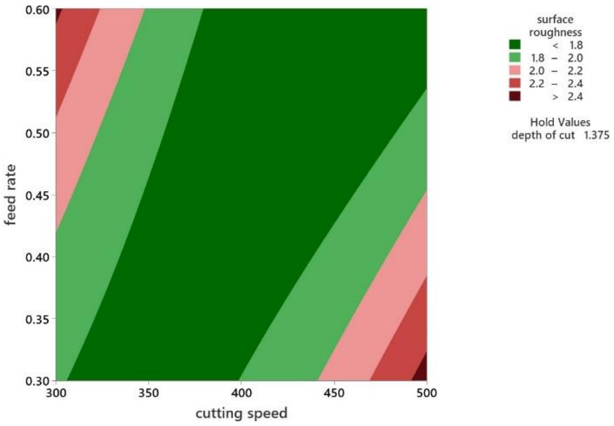

Fig.7: Contour plot showing the effect of cutting speed (rpm) on feed rate (mm/rev.) on surface roughness (depth of cut 1.375 mm)

The interaction implications of the depth of cut and feed rate are shown in Fig. 8. The curve is elliptical in shape which infers that at a slower feed rate and higher depth of cut, the surface roughness value is less than 1.8 µm and it gives better performance than any other combination of cutting velocity and depth of cut. At 0.30 millimeter/revolution and 1.5 mm depth of cut, the dark green shaded area illustrates the potential of minimal surface roughness. These obtained values of cutting velocity, depth of cut and feed rate justified the values predicted from the confirmation experiment and it proposes that the best combination of cutting parameters consists of a cutting velocity of 400 rpm, feed rate of 0.3 millimeter/revolution and depth of cut as 1.5 mm (table 2) the predicted surface roughness is close to the experimental value. The optimal value of R_a was 1.64 µm as shown in table 6 is obtained at cutting speed (V_c) of 400 rpm, feed of 0.3 mm/rev and depth of cut of 1.5 mm as optimum value of input parameters.

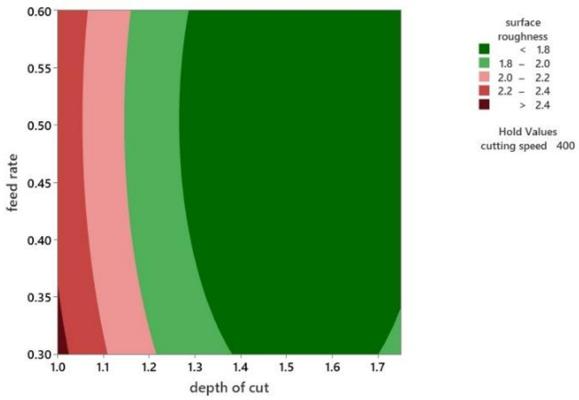

Fig.8: Contour plot showing the effect of depth of cut (mm) on feed rate (mm/rev.) on surface roughness (cutting velocity 400 rpm)

4. Conclusions

For analyzing experimental data, the Taguchi approach is a common and successful method. This methodology may be used to enhance any process. The DOE-Taguchi approach is used in this study to optimize machining settings to reduce surface roughness. The experiment's results reveal the optimal value of machining parameters, as well as the related rank: speed – 400 rpm – rank 1, feed rate – 0.3 millimeter/revolution – rank 2, depth of cut – 1.5 mm – rank 3. The surface roughness is 1.64 µm as a result of these characteristics. The most significant contributor to surface roughness is cutting velocity (32.81%), followed by feed rate (31.22%) and depth of cut (28.96%), according to ANOVA results. The surface roughness of FRP diminishes at first and subsequently grows when the spindle speed is increased. The surface roughness decreases initially, and then rises when the depth of cut is raised; however, when the feed rate is increased, the roughness of the surface of the FRP decreases. The experimental data obtained in present study show close relation with the data obtained from the predicted model.

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