MATHEMATICAL MODELLING FOR RADIAL OVERCUT ON MECHANICAL MICRO DRILLING OF CFRP-TI6AL4V STACK COMPOSITE BY RESPONSE SURFACE METHODOLOGY

Abstract

Response surface approach is used in this work to estimate radial overcut in the mechanical micro drilling process for CFRP-Ti6Al4V stack composite. To investigate the radial overcut, spindle speed, feed rate, and MQL flow rate are used as input process parameters. The central composite design (CCD) approach was used to plan the tests. A mathematical model was constructed after 20 tests to link the impacts of various machining factors with radial overcut. ANOVA at the 5% level of significance yielded the significant coefficients. Based on the data, it was discovered that spindle speed has a substantial influence on radial overcut. The projected findings based entirely on established models are found to be in good agreement with the expected values, with the coefficient of determination 0.7482 for radial overcut fitting the experimental data relatively well.

Keywords: Mechanical micro drilling, Radial overcut, CFRP/Ti6Al4V, Central composite design, Response surface methodology

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I. INTRODUCTION

In aerospace, CFRP-Ti6Al4V stack composite is utilized for engine cowlings, wing connections, wing panels, and nacelles. A 0.8 mm to 1.25 mm thick sheet of CFRP/Ti alloy is utilized for the cowling of the high performance engine of the 757 Dream liner, Falcon 900 business jet, Airbus A320, and F-16XL aircraft.

Modern composite materials like CFRP/Ti stack, which have amazing structural properties including a high strength-to-weight ratio, precise corrosion resistance, high layout flexibility, and others, are widely used in the aircraft industry today. The stacked composite may provide the combined structural benefits of each stacked phase while minimizing their individual weaknesses since it is made up of two different elements, CFRP and Ti alloy. For instance, the Ti alloy displays strong strength-to-weight ratio, excellent fracture resistance, isotropic behavior, and exhibits good reparability whereas the CFRP composite exhibits high specific stiffness, superior corrosion resistance, and remarkable fatigue strength. While the lack of low impact energy and repairable difficulties of composites are often avoided, the lack of fatigue strength and corrosion resistance of metals are frequently addressed by the metal alloy-to-composite alliance in a layered composite structure. [1-3]

Mechanical micro drilling is capable of producing minute holes as long as the tool's surface is tougher than the workpiece. This method involves repeatedly inserting and removing the drill from the hole, which creates a hole. The technique's potential may be seen in its ability to drill holes as small as 50 micrometres in metals, plastics, and polymers. Drill bits are used to cut holes in soft metals such as brass and copper. These drill bits are made of high-speed steel, tungsten, and other hard materials. Because more tiny and micro gadgets are being used, there is a growing demand for micro drilling, or creating holes that are smaller than 1 mm in diameter. miniature drilling is most commonly used in the automotive, aeronautics, electronics, and therapeutic domains. [4-5]

Several studies looked on mechanical micro-drilling of challenging materials. According to a study by R Landge et al., mechanical micro-drilling of brass material was evaluated experimentally using speed, feed, hole depth, and machining time as input machining parameters. The mathematical models for the MRR response were developed using response surface techniques. [6]

A work on the optimization of mechanical micro-drilling of CFRP employing spindle speed, feed rate, and drill diameter as input machining parameters was written by K. Shunmugesh et al. Mathematical models for the circularity and cylindricity errors were developed using the Taguchi technique. Low feed rate and high spindle speed are used to reduce circularity and cylindricity errors. [7]

In order to create, enhance, and optimize processes, the Response Surface Methodology (RSM) combines several input variables and analyses how their intricate connections affect the performance of the response variables as a whole. [10-11]. RSM creates the version utilising a statistical layout of test techniques, such the central composite design, and then mounts ANOVA checks to measure the performance of the recommended model. To observe how input variables impact responses, 3D response graphs can be employed. The RSM technique has been used extensively in studies to assess the effectiveness of industrial processes. [8-9], [12-13]

The literature study found no published research on the mechanical micro-drilling of CFRP-Ti6Al4V stack material. In order to produce a mathematical radial overcut using input parameters like spindle speed, feed rate, and MQL flow rate, the response surface technique is used in this study. The suitability of the developed model was assessed using an ANOVA test, and the impact of machining parameters on radial overcut was investigated via 3D response graphs.

II. EXPERIMENTAL DETAILS

The studies were carried out on an Interface design associates private limited, India, SMD10B CNC micro drilling machine. The machine's aerostatic spindle has a capability of 6001 rpm to 60000 rpm. Lubricant oil was brown transparent emulsified oil. CFRP and Ti6Al4V grade 5 work pieces were employed in the trials. The mechanical characteristics of Ti6Al4V and CFRP are shown in Tables 1 and 2.

Table 1: Mechanical properties of Ti6Al4V

Work piece (Young's modulus)	Density(kg/m3)	Hardness HV	Yield strength (MPa)	Tensile strength (MPa)	Thermal conductivity (W/m K)
Mechanical properties Ti-6Al-4V (120 GPa)	4420	349	880	950	6.7

Table 2: Mechanical Properties of CFRP

Properties	value
Density, g/cm^3	1.9
Young's Modulus, GPa	250
Shear Modulus, GPa	110
Uniform Elongation, %	1.9
Poisson's Ratio	0.33

CFRP and Ti6Al4V were stacked using Araldite AW134 Epoxy resin. T5401 grade - TiN coated tungsten carbide (coating thickness 0.2-0.5 micron) was employed for the current investigation. For the purposes of this investigation, a micro drill with a diameter of 0.4 mm and a point angle of 140 degrees was used..

Figure 1 shows the diameter of holes generated in the work material measured using an optical microscope (ALICONA Infinite focus). The Radial overcut is described by

Veenaraja et al. (2013) as half the difference between the diameter of the hole created and the diameter of the tool.[15]

$$Radialovercut = \frac{d_{jt} - d_t}{2} \quad (1)$$

Here, dt denotes the tool's diameter whereas djt denotes the size of the hole the tool left in the workpiece.

III. EXPERIMENTAL DESIGN AND PARAMETER SELECTION

The response surface methodology (RSM), which investigates how the performance of the response variables is influenced by the extensive interconnections of the input variables, is an excellent tool for building, improving, and optimizing processes. The response surface is often characterized by the following equation [14]:

$$Y = \beta_0 + \sum_{i=1}^{s} \beta_i \chi_i + \sum_{i=1}^{s} \beta_i \chi_i + \sum_{i=1}^{s} \beta_{ii} \chi_i^2 + \sum_{i=j}^{s} \beta_{ij} \chi_i \chi_j + \varepsilon \quad (2)$$

Table 3: Selected machining parameter and its levels

Name	Units	Lowest	Low	Centre	High	Highest
Spindle Speed	rpm	26591	30000	35000	40000	43408
Feed Rate	mm/min	1.03	1.2	1.45	1.7	1.87
MQL flow rate	ml/hr	99	150	225	300	351

RSM creates the model using statistical design of experiments methodologies such as the central composite design (CCD), and then uses ANOVA tests to assess how well the proposed model works. The trials were built using the experimental design method known as the CCD approach. The coefficients of the regression model may be calculated from the experiment results using the statistical tool Design Expert 13.0. Based on the literature on mechanical micro drilling study and the operating characteristics of the selected machine, spindle speed, feed rate, and MQL flow rate were chosen as the machining parameters for this work. Table 3 shows the selected machining parameters and their levels.

Table 4: CCD design layout and experimental results

	Factor 1	**Factor 2**	**Factor 3**	**Response**
Run	A:Spindle speed	B:Feed rate	C:MQL flow rate	Radial overcut
	RPM	mm/min	ml/hr	
1	30000	1.2	150	3.45
2	40000	1.2	150	28.24
3	30000	1.7	150	12.6
4	40000	1.7	150	15.7
5	30000	1.2	300	9.21
6	40000	1.2	300	11.13

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7	30000	1.7	300	17.6
8	40000	1.7	300	20.8
9	26591	1.45	225	3.35
10	43408	1.45	225	32.25
11	35000	1.02955	225	25.51
12	35000	1.87045	225	20.11
13	35000	1.45	98.8655	2.36
14	35000	1.45	351.134	7.21
15	35000	1.45	225	5.12
16	35000	1.45	225	11.56
17	35000	1.45	225	8.35
18	35000	1.45	225	0.11
19	35000	1.45	225	8.35
20	35000	1.45	225	19.56

IV. EXPERIMENTAL RESULT AND DISCUSSION

A total of 20 experimental runs for the CCD were performed, according to the input data in Table 4. As illustrated in Fig. 1, an optical microscope (ALICONA) may be used to measure the diameter of machined holes on work materials. The output response, or radial overcut, is then calculated for each run and reported in Table 4.

Figure 1: Measuring diameter of machined micro holes on work material by ALICONA optical microscope.

1. **Development of Mathematical Model for Radial Overcut and ANOVA:** The Design Expert software and the pertinent experimental data from Table 4 were used to create the mathematical model, which was used to relate how the machining settings affected the size of the radial overcut. The quality of fit of the model must be assessed before data analysis may proceed. The tests for the regression model's significance, the significance of the model coefficients, and the test for poor fit are all a part of the model adequacy

checking. Analysis of variance (ANOVA) is used to achieve this goal. The quadratic model is statistically significant for radial overcut analysis, according to the fit summary. ANOVA Table 5 presents the findings of the quadratic model for radial overcut.

The model appears remarkable based on its Model F-value of 3.30. Just 0.01% of the time may noise cause a "Model F-Value" of this size. Table 5's "Prob> F" values indicate that model terms with 95% confidence intervals less than 0.05 are significant. A, AB, and B2 were significant model variables in this situation. The model terms are not significant if the value is greater than 0.1000. If your model has many unnecessary words (apart from those necessary to maintain hierarchy), model reduction may help it.

The "Lack of Fit F-value" of 0.8510 indicates that there is no statistically significant difference between the Lack of Fit and the pure error. A "Lack of Fit F-value" this high might be due to noise with a 56.81% possibility. It also displays the R-Squared and corrected R-Squared values for the model. The better the response model matches the experimental data, the closer R2 is to unity. According to the calculated R-Squared value of 0.7482, the model explains around 74.82% of the ROC variance. A fair agreement can be drawn between the "Pred R-Squared" value of 0.4624 and the "Adj R-Squared" value of 0.5215. Furthermore, the "Adeq Precision" score of 5.5638 for this model suggests a sufficient signal and is higher than 4. Utilise the design space's navigational tools.

Table 5: Analysis of variance for radial overcut model

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	
Model	1170.52	9	130.06	3.30	0.0383	**significant**
A-Spindle speed	487.63	1	487.63	12.38	0.0056	
B-Feed rate	2.29	1	2.29	0.0581	0.8144	
C-MQL flow rate	3.50	1	3.50	0.0888	0.7719	
AB	52.07	1	52.07	1.32	0.0421	
AC	64.81	1	64.81	1.64	0.2286	
BC	57.51	1	57.51	1.46	0.2548	
A^2	131.91	1	131.91	3.35	0.0972	
B^2	331.59	1	331.59	8.42	0.0158	
C^2	35.80	1	35.80	0.9086	0.3630	
Residual	393.99	10	39.40			
Lack of Fit	181.14	5	36.23	0.8510	0.5681	**not significant**
Pure Error	212.85	5	42.57			
Cor Total	1564.51	19				
R^2	0.7482					
Adjusted R^2	0.5215					
Predicted R^2	0.4624					
Adeq Precision	5.5638					

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Backward elimination is used to remove non-significant terms from the fitted quadratic model before it is adjusted for ROC. The following is how the final ROC quadratic model is arrived at:

$$ROC = 8.86 + 10.05A - 7.21AB + 13.54B^2$$

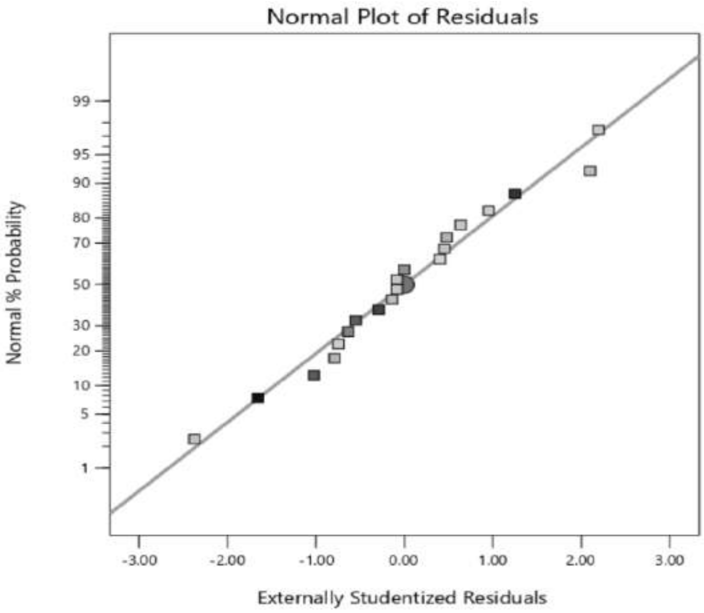

Figure 2: Normal probability plot for radial overcut

When the data's underlying assumptions about normality are tested, it can be seen in Fig. 2 that every point on the normal plot is nearly straight.

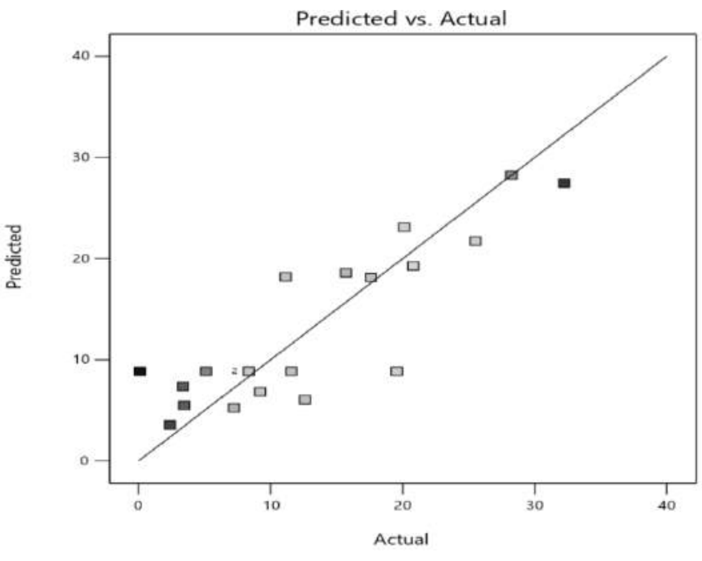

Figure 3: Comparison with predicted radial overcut with experimental data

Additionally, each experimental data set is contrasted with the projected data derived from the model and shown in Fig. 3. It is evident that the expected values for the radial overcut reasonably match the experimental results.

2. **Effect of Machining Parameters on the Radial Overcut:** Radial overcut is an intrinsic characteristic of the micro drilling process that cannot be avoided, even when appropriate compensations are supplied at the tool design. Overcut should be kept to a minimum in order to obtain improved precision in the mechanical micro drilling process. As a result, the parameters impacting the radial overcut must be identified. Figure 4 depicts how spindle speed and feed rate affect radial overcut. Minimum radial overcut occurs with a medium spindle speed and a medium feed rate. It can be seen that the medium level of feed rate is optimum for reducing radial overcut.

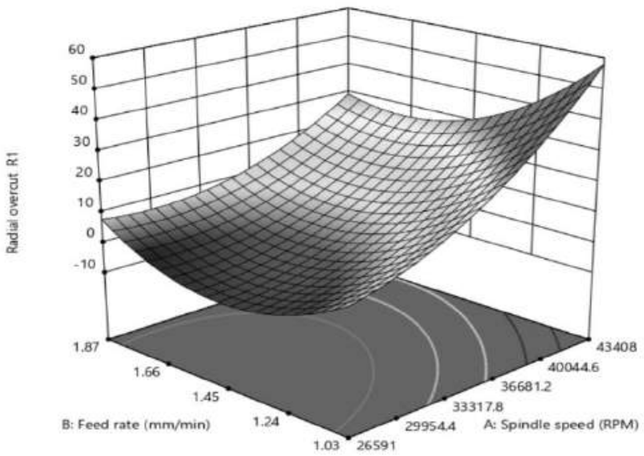

Figure 4: Response surface plot for radial overcut Vs spindle speed and feed rate

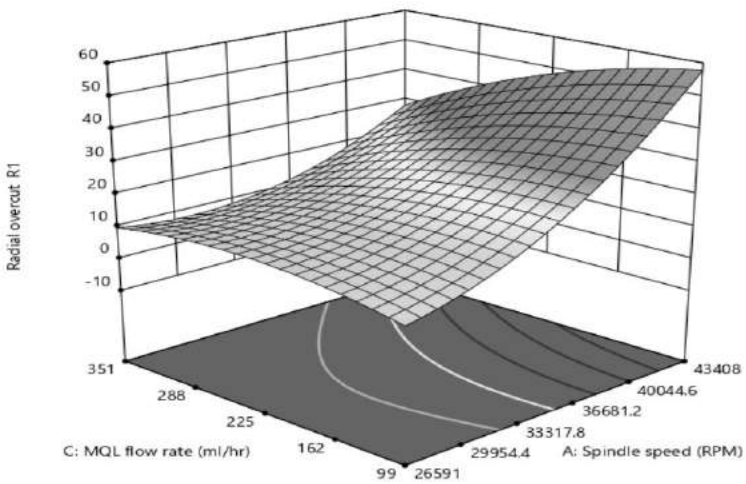

Figure 5: Response surface plot for radial overcut Vs spindle speed and MQL flow rate

Figure 5 depicts the expected surface response for radial overcut in relation to spindle speed and MQL flow rate. It can be seen that lowest radial overcut occurs at a low MQL flow rate and at the middle spindle speed. It can be seen that increasing the spindle speed increases the radial overcut.

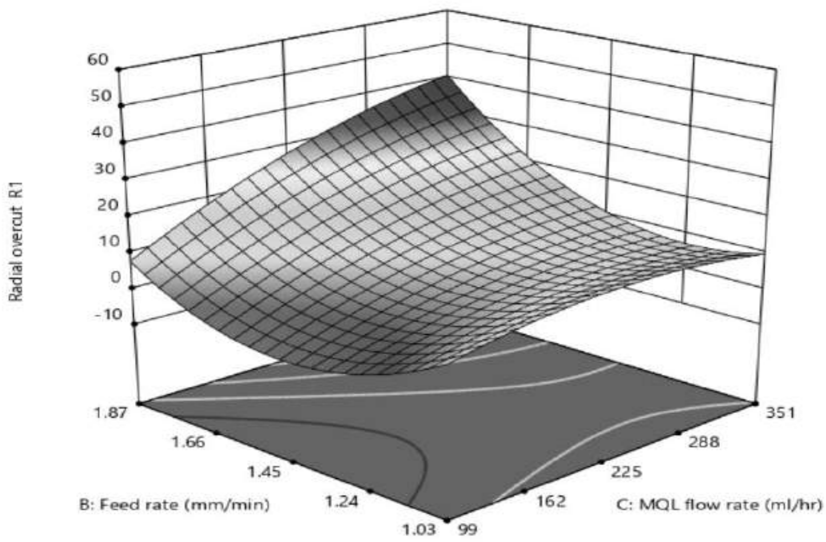

Figure 6: Response surface plot for radial overcut Vs feed rate and MQL flow rate

The influence of feed rate and MQL flow rate on radial overcut is depicted in Figure 6. It is evident that the smallest radial overcut occurs for feed rates around the middle of the range and flow rates near the middle of the range, as well as spindle speeds near the centre of the range. It is obvious that MQL flow rate influences radial overcut more than feed rate and spindle speed.

Spindle speed is directly related to the centrifugal force acting on the lubricating fluid contained in the gap between tool and workpiece, which contains debris particles, according to graph trends. As a result, increasing the spindle speed somewhat reduces radial overcut. greater feed rate increments with rapid increases in spindle speed are attributable to greater friction between tool and work piece. As a result of the increased heat generation and wear, a bigger radial overcut occurs.

V. CONCLUSION

An effort was made in this work to use response surface methods to forecast radial overcut in mechanical micro drilling of CFRP-Ti6Al4V stack composite material. Twenty tests were successfully carried out for three input parameters at five levels using the central composite design (CCD) approach. Using the experimental data, the mathematical model for radial overcut was constructed on the basis of RSM. ANOVA findings demonstrate that spindle speed is a very significant parameter, whereas feed rate and MQL flow rate are non-significant parameters when radial overcut reaction is taken into account. With a coefficient of determination of 0.7482 for radial overcut, the projected values match the experimental

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data quite well. According to the response surface plots, the intermediate level of spindle speed and feed rate significantly reduces radial overcut. The results of this study show that response surface approach can be utilized to successfully simulate the input machining parameters of the mechanical micro-drilling process for CFRP-Ti6Al4V stack composite. The findings can be expanded in the future to build models for additional reactions such as hole taper and delamination factor.

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