Mathematical Modelling for Radial Overcut on Mechanical Micro drilling of CFRP-Ti6Al4V Stack Composite by Response Surface Methodology

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ABSTRACT

In the present study, Response surface methodology is applied for prediction of radial overcut in mechanical micro drilling process for CFRP-Ti6Al4V stack composite. Spindle speed, feed rate and MQL flow rate are considered as input process parameters to study the radial overcut. The experiments were planned as per central composite design (CCD) method. After conducting 20 experiments, a mathematical model was developed to correlate the influences of these machining parameters and radial overcut. The significant coefficients were obtained by performing ANOVA at 5% level of significance. From the obtained results, It was found that spindle speed have significant effect on the radial overcut. The predicted results based totally on developed models are discovered to be in good agreement with the expected values fit the experimental results moderately properly with the coefficient of determination 0.7482 for radial overcut.

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

I. INTRODUCTION

CFRP-Ti6Al4V stack composite is used in airspace industry for engine cowlings, wings connection, wing panels and nacelles. CFRP/Ti alloy stack of about 0.8 mm to 1.25 mm thick sheet is used for cowling of high performance engine of 757 Dreamliner, Falcon 900 business jet, Airbus A320, F-16XL aircraft.

CFRP/Ti stack is an advanced composite material that has been extensively used in present day aerospace industry due to its superior mechanical properties and exceptional structural functions such as high strength-to-weight ratio, exact corrosion resistance, high layout flexibility, and so forth. The stacked composite which consists of two disparate constituents that is CFRP and Ti alloy, can provide combined structural advantages of each stacked phase while their individual weaknesses are significantly avoided. For example, the Ti alloy has good strength-to-weight ratio, high fracture resistance, isotropic behavior, and exhibits good reparability while the CFRP composite shows high specific stiffness, superior corrosion resistance, and excellent fatigue strength. The combination of the metal alloy-to-composite alliance in a stacked composite structure generally overcomes the dearth of fatigue strength and corrosion resistance of metals, and avoids the lack of low impact energy and reparable trouble of composites. [1-3]

Mechanical micro drilling is capable of fabrication of micro holes provided that the device has hardness more than that of the work piece. This procedure makes use of peck cycle where in the drill is repeatedly inserted and withdrawn from the hole which leads to the creation of a hole. The potentiality of the technique may be visible through its ability to manufacture holes having diameter as small as 50μm, on substances like plastics and polymers as well as metals. Drill bits are product of hard materials ranging from high speed steel, tungsten and other carbides to machine holes on soft metals like brass and copper. The demand for micro drilling that is drilling holes of diameter much less than 1 mm is gaining significance because of the growth within the use of miniature and micro gadgets. The predominant areas of application of micro drilling are car, aeronautics, electronics and clinical fields. [4-5]

Some researchers worked on mechanical micro drilling of difficult-to-cut materials. R landge et al. reported on an experimental investigation of micro drilling of brass material using the mechanical micro drilling by considering speed, feed, depth of hole and machining time as input machining parameters. Mathematical models were developed for the MRR response using response surface methodology. [6]

K shunmugesh et al. reported on optimization of mechanical micro drilling of CFRP by considering spindle speed, feed rate and drill diameter as input machining parameters. Mathematical model were developed for the circularity error and cylindricity error using taguchi methodology. Minimum feed rate and maximum spindle speed minimizes the circularity and cylindricity errors. [7]

Response surface methodology (RSM) is an effective tool for developing, enhancing, and optimizing the procedures by way of combining numerous input variables and verify how their complex interactions affect the overall performance of the response variables [10-11]. RSM uses statistical layout of test strategies, such as the central composite design for developing the version and the performance of the proposed model is then mounted by way of ANOVA checks. 3D response graphs can be used to observe the impact of input variables on responses. Plenty of researchers have used RSM technique to assess the performance of manufacturing processes. [8-9], [12-13]

From the literature study, it was understood that no research work has been reported in mechanical micro drilling of CFRP-Ti6Al4V stack material. So, In this study, response surface methodology is used for the development of a mathematical of radial overcut with spindle speed, feed rate and MQL flow rate as input parameters. The adequacy of the developed model has been evaluated by ANOVA test and the effect of machining parameters on radial overcut has been investigated through 3D response graphs.

II. EXPERIMENTAL DETAILS

The experiments were carried out on SMD10B CNC micro drilling machine manufactured by Interface design associates private limited, India. Aerostatic spindle is provided 6001 rpm to 60000 rpm capacity for the machine. Brown translucent emulsion oil was used as lubrication oil. The workpiece material used for the experiments was CFRP and Ti6Al4V grade 5. Table 1 and 2 depicts the mechanical properties of Ti6Al4V and CFRP material.

Table 1. Mechanical properties of Ti6Al4V

Workpiece (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

Araldite AW134 Epoxy resin was used for stacking of CFRP and Ti6Al4V. Tool material used for the present experiment was T5401 grade – TiN coated tungsten carbide (Coating thickness 0.2-0.5 micron). Micro drill with a diameter of 0.4 mm and 140 degree point angle was selected for the purpose of this study.

The diameter of holes produced in the work material has been measured by using optical microscope (ALICONA Infinite focus) as shown in Figure 1. According to Veenaraja et al. (2013), the Radial overcut is defined as half the difference between the diameter of the hole generated and the diameter of the tool.[15]

$$Radial\ overcut = \frac{d_{jt} - d_t}{2}$$

(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

A effective tool for creating, enhancing, and optimising processes is the response surface methodology (RSM), which examines how the performance of the response variables is impacted by the intricate interconnections of the input variables. The response surface is typically described by an equation of the following type [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 develops the model using statistical design of experiments approaches, such as the central composite design (CCD), and then utilises ANOVA tests to determine how well the suggested model performs. The experimental design method known as the CCD approach served as the foundation for the experiments. With the aid of the statistical programme Design Expert 13.0, the coefficients of the regression model may be ascertained from the findings of the experiment. Spindle speed, feed rate, and MQL flow rate were selected as the machining parameters for this work based on literature on mechanical micro drilling research and the working characteristics of the selected machine. Table 3 displays the chosen machining settings 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
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

According to the input data in Table 4, a total of 20 experimental runs for the CCD were carried out. The diameter of machined holes on work materials can be measured using a optical microscope (ALICONA), as shown in Fig. 1. The output response, or radial overcut, is then determined for each run using Eqn. (1) and summarised in Table 4

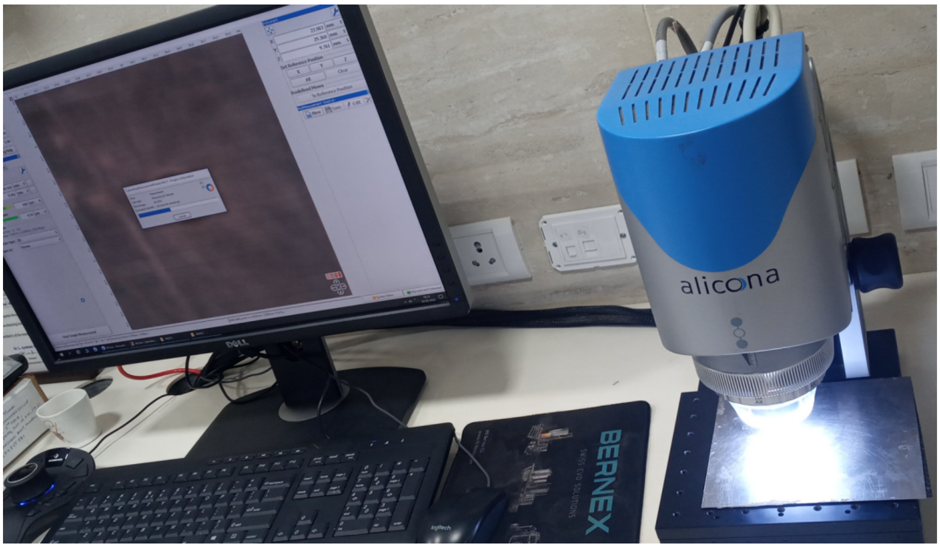

Fig.1 Measuring diameter of machined micro holes on work material by ALICONA optical microscope.

A. Development of Mathematical model for radial overcut and ANOVA

Using Design Expert software and the pertinent experimental data from Table 4, the mathematical model has been created to link the impacts of the machining parameters on the size of radial overcut. For data analysis, evaluating the model's goodness of fit is crucial. The tests for the regression model's significance, the model coefficients' significance, and the test for poor fit make up the model adequacy checking. Analysis of variance

(ANOVA) is carried out for this aim. The quadratic model is statistically significant for radial overcut analysis, according to the fit summary. In ANOVA Table 5, the findings of the quadratic model for radial overcut are presented.

The model is suggested to be significant by the Model F-value of 3.30. A "Model F-Value" this large might happen owing to noise only 0.01% of the time. Model terms that are smaller than 0.05 (95% confidence) have values of "Prob > F" in Table 5, indicating that they are significant. In this instance, key model terms were A, AB and B^2. Model terms are not significant if the value is higher than 0.1000. Model reduction may enhance your model if it has a lot of unnecessary terms (except those needed to maintain hierarchy).

The "Lack of Fit F-value" of 0.8510 indicates that there is no significant difference between the Lack of Fit and the pure error. A "Lack of Fit F-value" this large could be caused by noise with a 56.81% probability. Additionally, it displays the model's R-Squared and adjusted R-Squared values. The better the response model fits the experimental data, the closer R2 is to unity. Here, the calculated R-Squared value of 0.7482 suggests that the model accounts for roughly 74.82% of the variance in the ROC. The "Pred R-Squared" of 0.4624 and the "Adj R-Squared" of 0.5215 are reasonably in accord. Additionally, this model's "Adeq Precision" score, which is 5.5638, suggests a sufficient signal and is greater than 4 in this model. To move around the design space, utilise this model.

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					

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:

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

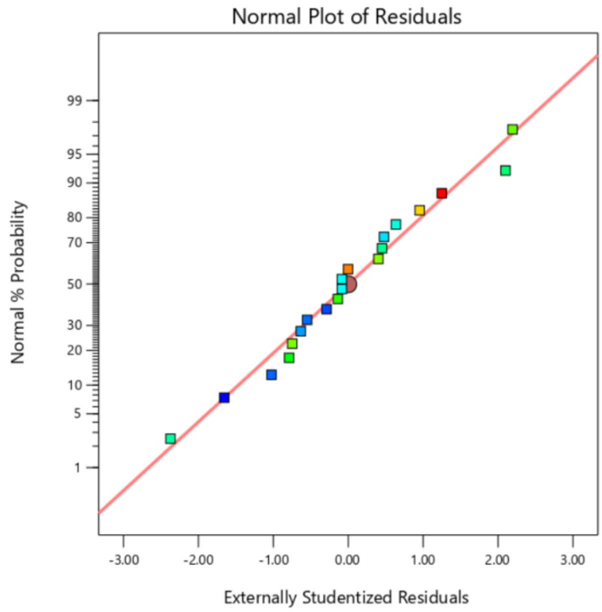

Fig. 2. Normal probability plot for radial overcut

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.

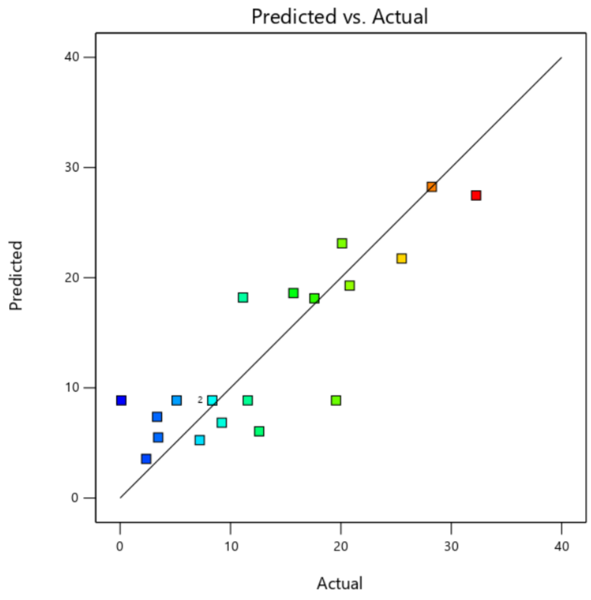

Fig. 3. Comparison with predicted radial overcut with experimental data

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.

B. Effect of machining parameters on the radial overcut

Radial overcut is the inherent parameter to the micro drilling process which is unavoidable though suitable compensations are provided at the tool design. In order to achieve the greater accuracy in mechanical micro drilling process overcut should be minimum. Hence, parameters affecting the radial overcut are essential to recognize. Figure 4 shows the influence of spindle speed and feed rate on radial overcut. Minimum radial overcut occurs for middle level of spindle speed and a middle level of feed rate. It can be noticed that middle level of feed rate is best for lower radial overcut.

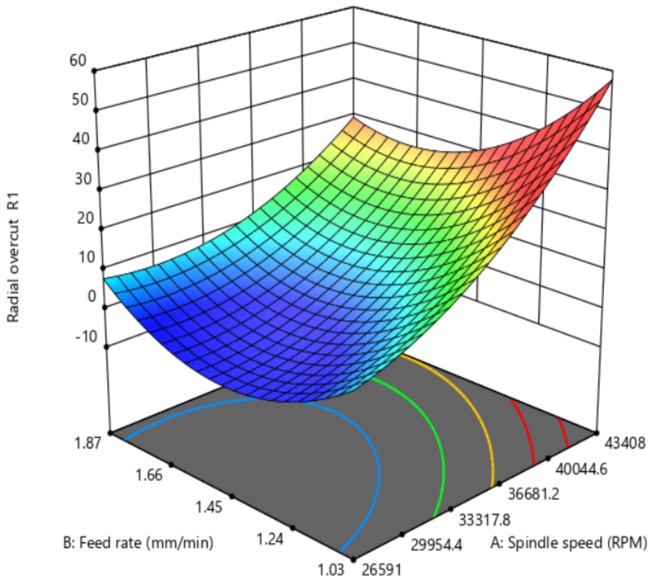

Fig. 4. Response surface plot for radial overcut Vs spindle speed and feed rate

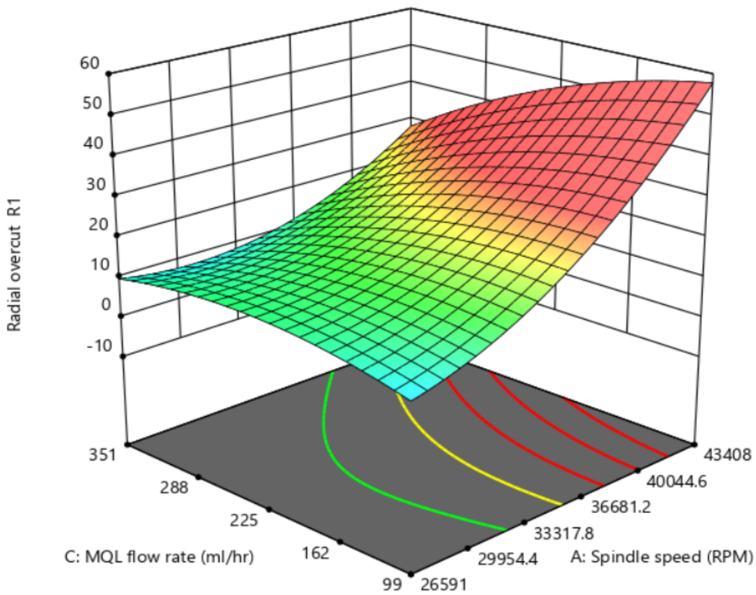

Fig. 5. Response surface plot for radial overcut Vs spindle speed and MQL flow rate

The estimated surface response for radial overcut in relation to spindle speed and MQL flow rate shown in figure 5. It can be seen that minimum radial overcut occurs for a minimum level of MQL flow rate and near to the middle level of spindle speed. It can be noticed that higher level of spindle speed gives maximum the radial overcut.

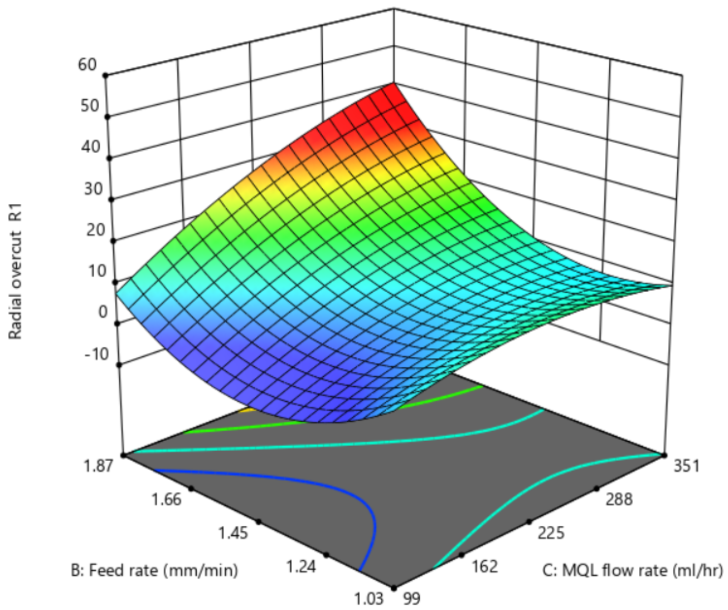

Fig. 6. Response surface plot for radial overcut Vs feed rate and MQL flow rate

Figure 6 shows the effect of feed rate and MQL flow rate on radial overcut. It is clear that the minimum radial overcut occurs for near to the middle level of feed rate and near to middle level of flow rate and also note that the middle level of spindle speed are the suitable condition for lower radial overcut. It is cleared that radial overcut depends more on MQL flow rate than on feed rate and spindle speed.

According to trends in graph, Spindle speed is directly proportional to the centrifugal force acting on the lubrication fluid present in the gap between tool and workpiece, which contains debris particles. Therefore, when the spindle speed slightly increases, result minimize radial overcut. When higher increment in feed rate with fast increase in spindle speed attributed to the higher friction between tool and work piece. Therefore, produce high heat generation and wear leads to the occurrence of larger radial overcut.

V. CONCLUSION

In this study, an attempt was made to apply response surface methodology for prediction of radial overcut in mechanical micro drilling of CFRP-Ti6Al4V stack composite material. Twenty experiments were conducted successfully for three input parameters at five levels as per central composite design (CCD) method. The mathematical model for radial overcut has been developed on the basis of RSM by utilizing the experimental results. ANOVA results show that spindle speed are highly significant parameter, while feed rate and MQL flow rate are non-significant parameters by considering radial overcut response. The predicted values match the experimental results reasonably well with the coefficient of determination of 0.7482 for radial overcut. From the response surface plots, it is cleared that middle level of spindle speed and feed rate minimizes the radial overcut considerably. This study demonstrates that response surface methodology can be successfully used to model input machining parameters of mechanical micro drilling process for CFRP-Ti6Al4V stack composite. In future the study can be extended for developing models for other responses like hole taper and delamination factor.

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