



THRUST FORCE, SURFACE ROUGHNESS AND OVALITY PREDICTION BY RSM IN DRILLING OF ALUMINIUM BASED METAL MATRIX COMPOSITES

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ABSTRACT

Drilling is one of the most economical and widely used conventional machining processes for making holes during assembly operations. Predictions of cutting forces and the quality of drilled holes for any set of cutting parameters are essential in optimal design and manufacturing of products. In this paper, thrust force and drilled hole surface characteristics during drilling of Al/SiC metal matrix composites using high speed steel have been studied. The thrust force is measured using drill tool dynamometer, drilled hole surface roughness using Sufcom- surface measuring instrument and ovality of the hole using profile projector. Linear regression equations are developed using Response surface methodology with an objective to establish a correlation between the selected drilling parameters with the quality characteristics of the drilled holes. The predicted values are compared with experimental data and are found to be in good agreement.

Keywords: ovality, RSM, metal matrix composites, ANOVA, surface roughness, thrust force.

INTRODUCTION

Metal matrix composites are unique material fabricated by reinforcement of ceramic particles in to a tough metal matrix. In the last few decades, research has shifted towards composite materials to meet the global demand for high strength to weight ratio, good performance, ecofriendly, corrosion and wear resistant materials [1]. But composites are not easy to drill as compared to conventional materials. Drilling is most widely used for joining different materials, due to the economic reason and applicability. Generally, the metal matrix composites contain Silicon carbide in particulate form. So, the cutting tool must be able to drill the composites with good quality. Also, the understanding of relationship among the various cutting parameters became necessary to identify the important parameters that influence the quality of drilling [2]. There are many factors that influence the quality of drilled holes in metal matrix composites. Most important factors among them are cutting parameters (Cutting speed and feed rate) and cutting configurations (Drill tool, tool diameter and tool geometry) [3] [4].

Yahya Altunpak *et al.* [4] carried out an experimental study on the drilling characteristics of Al/SiC/Gr hybrid metal matrix composites. P. Kishore Kumar *et al.* [5] carried out an investigation on the influence of thrust force and torque in drilling processes of Aluminum 6061-T6 alloy. A. Muniaraj *et al.* [6] carried out a study on the Influence of drilling parameters on thrust force in drilling of Al/SiC/Gr hybrid metal matrix composites. A. TASKESSEN *et al.* [7] carried out an analysis for optimization of drilling parameters for tool

wear and hole dimensional accuracy in and Aluminium based metal matrix composites.

The aim of this paper is to analyze the cutting parameters (Cutting speed and feed rate) and cutting configurations (Tool diameter) on thrust force, surface roughness of the drilled hole and ovality of the drilled hole in drilling of Al-10%/SiC metal matrix composites by HSS drill of 5 mm, 7.5 mm and 10 mm diameter with different spindle speed and feed conditions. Taguchi's L27 orthogonal array is used for conducting the experiments. The experimental results are analysed by response surface methodology using the software design expert version 7.0.0 and the prediction model is compared with the experimental results.

EXPERIMENTAL WORK

Composite specimen preparation

In this work, a metal matrix composite made up of 6061 aluminium alloy (including mass fractions: 5 % zinc, 3.5 % copper and 2.5 % of magnesium) as the matrix element and 10% weight fraction of SiC of particle size 50µm as the reinforcement element. The Al 6061 bar was cut into small pieces and melted in a graphite crucible. The required preheated quantity of matrix material was fed into the Furnace crucible and mixed uniformly using a ceramic stirrer with the help of a motor. The temperature was raised above the liquidus temperature of the aluminium alloy above 880 °C. Then the preheated SiC particles are poured into the semi liquid melt and again stirring was done with the help of the motor after keeping it in the furnace. At this stage stirring was carried out for about 30 minutes at an average stirring speed rate of 650 rpm. The



slurry was then poured into a preheated cast iron permanent mould. The solidified casting obtained after cooling is used as the test specimen.

Test set up and drilling process

The drilling tests are performed on Taiwan made ARIX-CNC vertical machining centre. Coolant was not used in all of the drilling tests. The dimensions of the work piece samples used for conducting the experiments were 100 mm×100 mm×10 mm. The machining parameters and types of drills are given in Table-1.

The Kirsler dynamometer is used to record the thrust force in the drilling of hybrid MMCs [8]. The dynamometer is connected to a 3-channel charge amplifier type through a connecting cable, which in turn is connected to the PC with a 37-pin cable from the A/D board. The thrust force from the dynamometer was amplified and fed through a data-acquisition system for electronic storage. The data-acquisition System is based on the dynaware software.

The surface roughness of the work piece hole was measured by using Kosaka - Surfcomer SE700 a surface roughness measuring instrument. The surface roughness was measured parallel to each hole axis [9] from various points and the average values of the measurements were evaluated and considered for analysis.

Ovality is one of the most important parameter to check hole quality performance. It is defined as a two

dimensional geometric tolerance that controls how much a feature can deviate from a perfect circle [10]. Measurement of Ovality is done by profile projector.

Response surface methodology

Response surface methodology (RSM) is a collection of experimental strategies, statistical and mathematical techniques that are useful for the analysis of problems in which the response of interest is influenced by various parameters and the objective is quality improvement and to minimize the response [11]. In response surface methodology, the quantitative relationship between the response of interest and the independent process variables is represented as follows

$$R = \Phi(f, s, d)$$

Where R is the response of interest, Φ is the response function, f is feed rate in mm/rev, s is spindle speed in rpm and d is the drill tool diameter in mm [12].

The working range of factors was set at five levels. The selected factors and their levels are shown in Table [13]. Analysis of variance is a statistical analysis method that describes about the nature of data. It is a method of portioning variability into identifiable sources of variations and the associated degrees of freedom in the experiment [14].

Table-1. Drilling parameters and limits.

Drilling parameters	Symbol	Unit	Limits		
			-1	0	1
Spindle Speed	s	rpm	600	1000	1400
Feed rate	f	mm/rev	0.05	0.1	0.15
Drill diameter	d	mm	5	7.5	10

RESULTS AND DISCUSSIONS

The experiments are planned to conduct as per L27 Orthogonal Array. Table chosen based on Taguchi's quality design method (Table-2). The Response Surface Methodology was performed to predict the thrust force,

surface roughness and ovality of the holes drilled in the metal matrix composite specimens. To analyze the relative significance of the drilling parameters like drill tool diameter (d), spindle speed (s) and feed rate (f), on the response of interest, ANNOVA was used.

**Table-2.** L27 Orthogonal array for MMC (Al6061 + 10% SiC) drilling with HSS tool.

Group No.	Drilling parameter			Responses		
	Diameter of drill (mm)	Speed (rpm)	Feed rate (mm/rev)	Thrust force (N)	Surface roughness (μm)	Ovality (%)
1	1	1	1	158.569	5.72	2.3
2	1	1	2	185.913	5.8	0.1
3	1	1	3	224.731	7.26	1.5
4	1	2	1	122.192	7.07	1.4
5	1	2	2	121.704	5.46	1.3
6	1	2	3	147.461	9.37	0.3
7	1	3	1	109.619	5.61	0.5
8	1	3	2	112.915	5.92	0.2
9	1	3	3	117.065	5.68	0.2
10	2	1	1	217.59	5.8	1.9
11	2	1	2	270.736	5.53	0.71
12	2	1	3	294.97	6.96	1.2
13	2	2	1	185.937	7.42	1.3
14	2	2	2	211.807	5.83	1.06
15	2	2	3	238.062	8.5	1.35
16	2	3	1	161.334	6.41	1.02
17	2	3	2	196.54	6.09	0.63
18	2	3	3	201.468	6.17	0.95
19	3	1	1	254.579	3.22	2.1
20	3	1	2	351.936	5.04	1.2
21	3	1	3	369.324	5.67	1.4
22	3	2	1	227.905	4.3	1.85
23	3	2	2	314.209	8.63	1.6
24	3	2	3	330.444	6.53	1.4
25	3	3	1	199.684	3.13	0.72
26	3	3	2	272.433	4.82	1.06
27	3	3	3	297.772	4.34	0.87

From the ANNOVA table for thrust force, Table-3, it is clear that the F value of 102.5 and the value of Prob > F is less than 0.0001 which indicates that the terms in the model are significant. The "R-Squared" value is 0.9819 which is in reasonable agreement. From the Table, it is concluded that the factors d, s, f and their interactions have significant effect on the thrust force. The final regression equation in terms of coded factors is given below.

$$\text{Thrust Force} = +220.57 + 73.23 * d - 36.64 * s + 32.44 * f + 1.97 * d * s + 18.04 * d * f - 9.38 * s * f - 2.14 * d^2 + 10.99 * s^2 - 12.09 * f^2$$

The ANNOVA Table for Surface roughness, Table-4, shows that the F value of 3.31 and the value of Prob > F is less than 0.0161 which indicates that the terms in the model are significant and in the ANNOVA table for ovality, Table-5, the F value is 3.79 and the value of Prob > F is less than 0.011 which indicates that the terms in the model are significant. The final regression equation in terms of coded factors for surface roughness is given as

$$\text{Surface Roughness} = + 7.42 - 0.68 * d - 0.16 * s + 0.66 * f - 5.833\text{E-}003 * d * s + 0.17 * d * f - 0.34 * s * f - 0.77 * d^2 - 1.50 * s^2 + 0.16 * f^2$$



The final regression equation in terms of coded factors for ovality of the drilled hole is given as

$$\text{Ovality} = +1.12 + 0.24 * d - 0.35 * s - 0.22 * f + 0.079 * d * s + 0.100 * d * f + 0.16 * s * f.$$
Table-3. ANNOVA table for thrust force.

Source	Sum of squares	df	Mean square	F Value	p-value Prob > F	
Model	1.463E+005	9	16251.92	102.50	< 0.0001	significant
A-Tool Diameter	96524.02	1	96524.02	608.79	< 0.0001	
B-Speed	24164.67	1	24164.67	152.41	< 0.0001	
C-Feed rate	18940.29	1	18940.29	119.46	< 0.0001	
AB	46.67	1	46.67	0.29	0.5945	
AC	3905.84	1	3905.84	24.63	0.0001	
BC	1056.92	1	1056.92	6.67	0.0194	
A^2	27.35	1	27.35	0.17	0.6831	
B^2	724.07	1	724.07	4.57	0.0474	
C^2	877.49	1	877.49	5.53	0.0310	
Residual	2695.37	17	158.55			
Cor Total	1.490E+005	26				

Table-4. ANNOVA table for surface roughness.

Source	Sum of squares	df	Mean square	F Value	p-value Prob > F	
Model	35.46	9	3.94	3.31	0.0161	significant
A-Tool Diameter	8.28	1	8.28	6.97	0.0172	
B-Speed	0.44	1	0.44	0.37	0.5488	
C-Feed rate	7.74	1	7.74	6.51	0.0207	
AB	4.083E-004	1	4.083E-004	3.434E-004	0.9854	
AC	0.33	1	0.33	0.27	0.6069	
BC	1.41	1	1.41	1.18	0.2918	
A^2	3.55	1	3.55	2.99	0.1020	
B^2	13.55	1	13.55	11.40	0.0036	
C^2	0.16	1	0.16	0.13	0.7200	
Residual	20.21	17	1.19			
Cor Total	55.67	26				

**Table-5.** ANNOVA table for ovality.

Source	Sum of squares	df	Mean square	F value	p-value Prob > F	
Model	4.63	6	0.77	3.79	0.0110	significant
A-Tool Diameter	1.08	1	1.08	5.28	0.0325	
B-Speed	2.18	1	2.18	10.69	0.0038	
C-Feed rate	0.85	1	0.85	4.19	0.0540	
AB	0.075	1	0.075	0.37	0.5502	
AC	0.12	1	0.12	0.59	0.4517	
BC	0.33	1	0.33	1.60	0.2198	
Residual	4.07	20	0.20			
Cor Total	8.70	26				

Table-6. Predicted results vs experimental results.

Group No.	Drilling parameter (Coded factors)			Responses					
	Drill dia (mm)	Speed (rpm)	Feed rate (mm/rev)	Thrust force (N)		Surface roughness (μm)		Ovality (%)	
				Expt	Pred	Expt	Pred	Expt	Pred
1	1	1	1	158.569	158.93	5.72	5.314	2.3	1.816
2	1	1	2	185.913	194.8	5.8	5.984	0.1	0.976
3	1	1	3	224.731	206.49	7.26	6.974	1.5	0.856
4	1	2	1	122.192	118.71	7.07	7.000	1.4	1.477
5	1	2	2	121.704	145.2	5.46	7.330	1.3	0.797
6	1	2	3	147.461	147.51	9.37	7.980	0.3	0.837
7	1	3	1	109.619	100.47	5.61	5.686	0.5	0.638
8	1	3	2	112.915	117.58	5.92	5.676	0.2	0.118
9	1	3	3	117.065	110.51	5.68	5.986	0.2	0.318
10	2	1	1	217.59	214.29	5.8	5.240	1.9	1.89
11	2	1	2	270.736	268.2	5.53	6.080	0.71	1.15
12	2	1	3	294.97	297.93	6.96	7.240	1.2	1.13
13	2	2	1	185.937	176.04	7.42	6.920	1.3	1.63
14	2	2	2	211.807	220.57	5.83	7.420	1.06	1.05
15	2	2	3	238.062	240.92	8.5	8.240	1.35	1.19
16	2	3	1	161.334	159.77	6.41	5.600	1.02	0.87
17	2	3	2	196.54	194.92	6.09	5.760	0.63	0.45
18	2	3	3	201.468	205.89	6.17	6.240	0.95	0.75
19	3	1	1	254.579	265.37	3.22	3.626	2.1	1.938
20	3	1	2	351.936	337.32	5.04	4.636	1.2	1.298
21	3	1	3	369.324	385.09	5.67	5.966	1.4	1.378
22	3	2	1	227.905	229.09	4.3	5.300	1.85	1.757
23	3	2	2	314.209	291.66	8.63	5.970	1.6	1.277
24	3	2	3	330.444	330.05	6.53	6.960	1.4	1.517
25	3	3	1	199.684	214.79	3.13	3.974	0.72	1.076
26	3	3	2	272.433	267.98	4.82	4.304	1.06	0.756
27	3	3	3	297.772	296.99	4.34	4.954	0.87	1.156



The predicted results were discussed through the Table-6 with experimental validation. The error obtained during this analysis was very less and so it was considered as acceptable model.

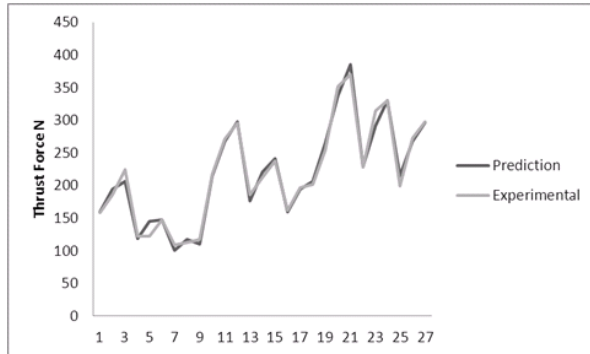


Figure-1. Thrust force predicted vs experimental.

The experimental values and predicted values for thrust force, surface roughness and ovality were plotted in the following graphs.

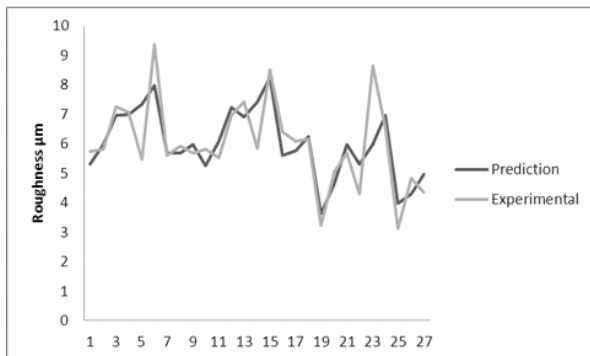


Figure-2. Surface roughness - predicted vs experimental.

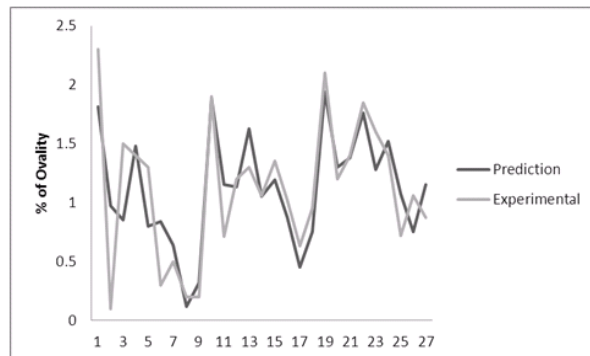


Figure-3. Ovality - predicted vs experimental.

Design-Expert® Software

Force
369.324
109.619

Force = 369.324
Std # 21 Run # 21
X1 = A: Tool Diameter = 10.00
X2 = B: Speed = 600.00

Actual Factor
C: Feed rate = 0.15

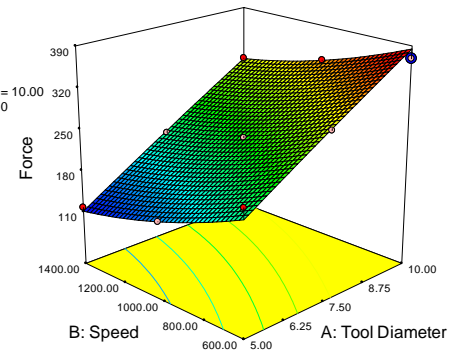


Figure-4. Estimated 3D response surface plot for thrust force at a feed rate of 0.15mm/rev.

Design-Expert® Software

Force
369.324
109.619

Force = 109.619
Std # 7 Run # 7
X1 = A: Tool Diameter = 5.00
X2 = B: Speed = 1400.00

Actual Factor
C: Feed rate = 0.05

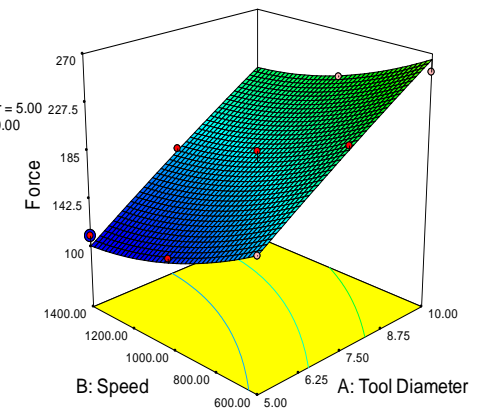


Figure-5. Estimated 3D response surface plot for thrust force at a feed rate of 0.05mm/rev.

Design-Expert® Software

Roughness
9.37
3.13

Roughness = 9.37
Std # 6 Run # 6
X1 = A: Tool Diameter = 5.00
X2 = B: Speed = 1000.00

Actual Factor
C: Feed rate = 0.15

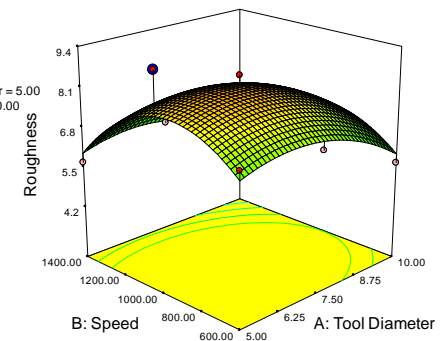


Figure-6. Estimated 3D response surface plot for roughness at a feed rate of 0.15mm/rev.

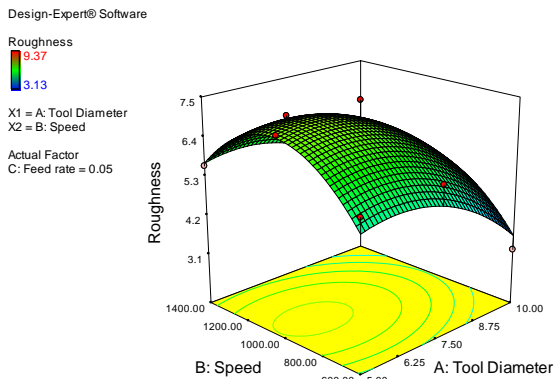


Figure-7. Estimated 3D response surface plot for roughness at a feed rate of 0.05mm/rev.

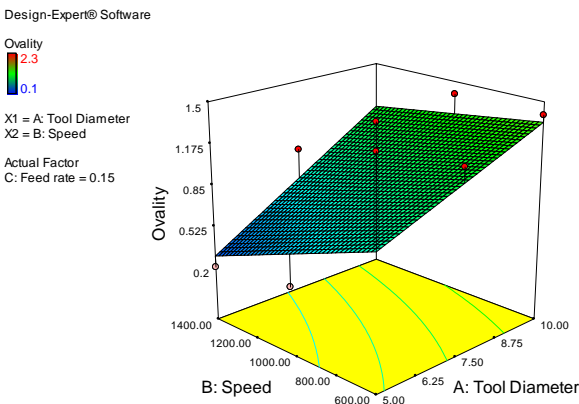


Figure-8. Estimated 3D response surface plot for ovality at a feed rate of 0.15mm/rev.

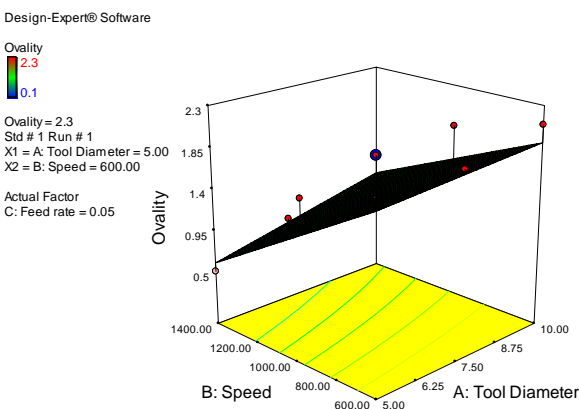


Figure-9. Estimated 3D response surface plot for ovality at a feed rate of 0.05mm/rev.

Figures 4 and 5 illustrate the surface plot for thrust force by varying the two variables, Spindle speed

and diameter of the drill by keeping the feed as constant. Similarly Figures 6 and 7 illustrate the surface plot for roughness and Figures 8 and 9 for ovality.

From the Figures 10, 11 and 12 it is clear that, as the drill diameter and feed rate increases the drilling force also increased, but spindle speed is having negative effect on thrust force.

The effect of these parameters on roughness of the drilled hole surface is shown in Figures 13, 14 and 15. It indicates that the effect of spindle speed on roughness is very less. But as the drill diameter increases, the roughness value decreased and the feed rate is having positive effect on roughness, that is, the roughness value increased along with feed rate.

Effect of the drilling parameters on ovality is shown in Figures 16, 17 and 18. Increasing spindle speed and feed rate decrease the percentage of ovality, but the drill diameter increases the ovality of the drilled hole.

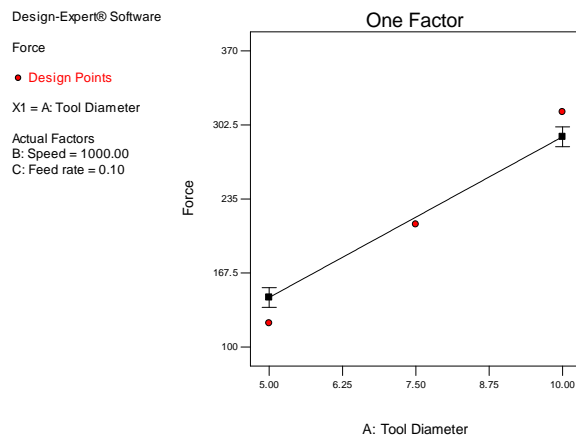


Figure-10. Effect of tool diameter on thrust force at constant speed and feed rate.

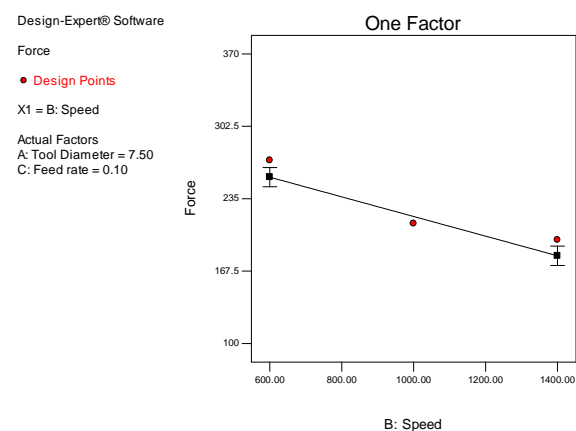


Figure-11. Effect of speed on thrust force at constant tool diameter and feed rate.

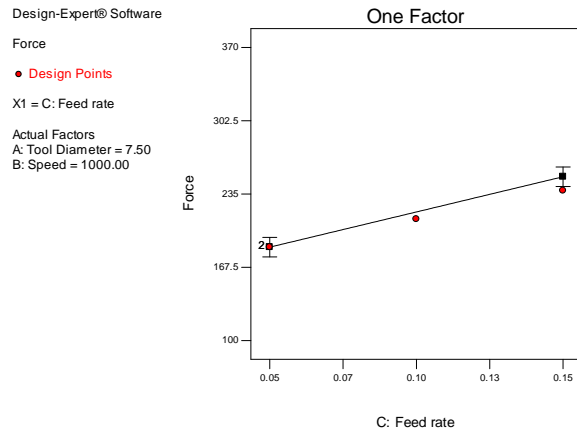


Figure-12. Effect of feed rate on thrust force at constant speed and tool diameter.

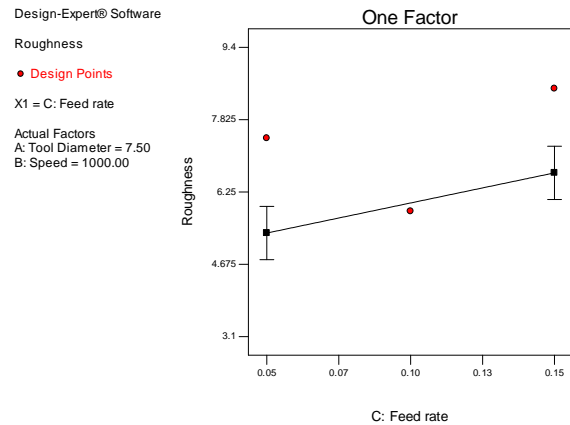


Figure-15. Effect of feed rate on roughness at constant speed and tool diameter.

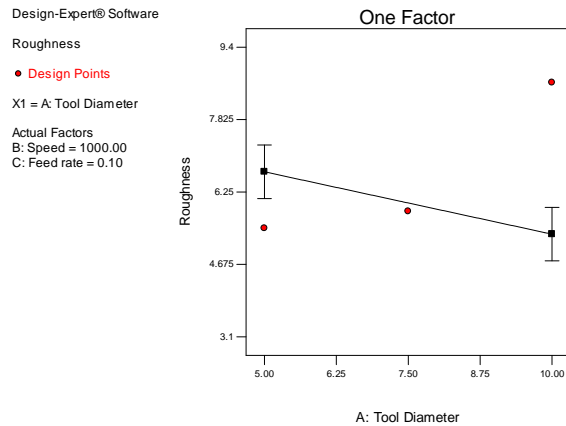


Figure-13. Effect of tool diameter on roughness at constant speed and feed rate.

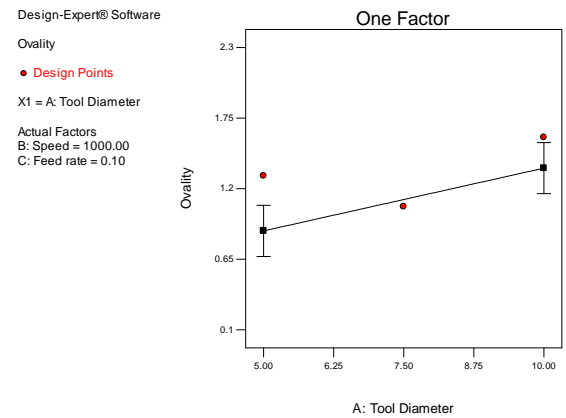


Figure-16. Effect of tool diameter on ovality at constant speed and feed rate.

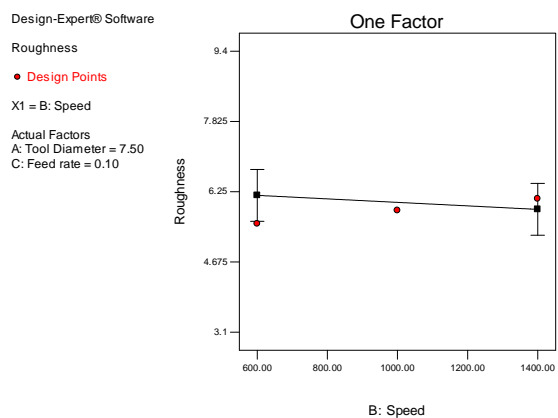


Figure-14. Effect of speed on roughness at constant feed rate and tool diameter.

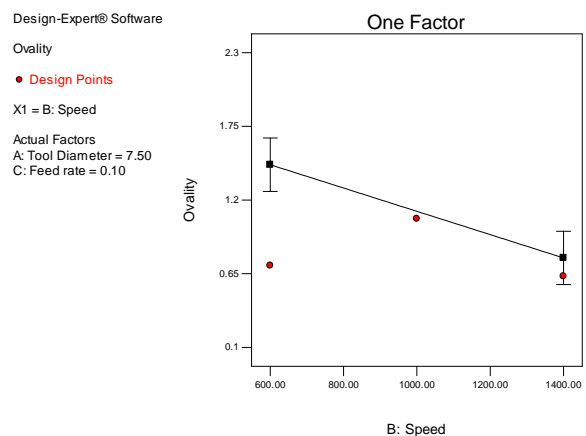


Figure-17. Effect of speed on ovality at constant feed rate and tool diameter.

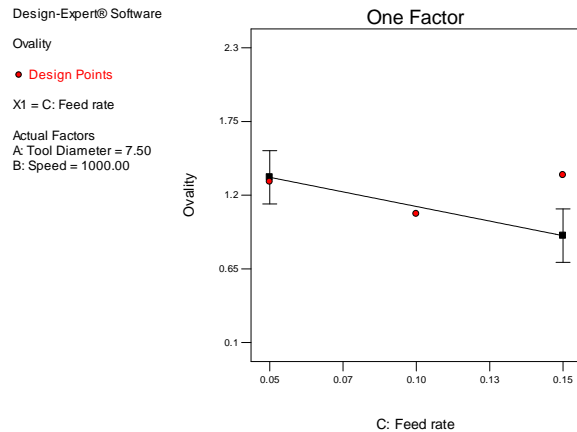


Figure-18. Effect of feed rate on ovality at constant speed and tool diameter.

The experimental results were analyzed with Analysis of Variance (ANOVA) which is used to investigate the influence of the parameters [1] affecting the performance and quality of drilling namely, drill diameter, spindle speed and feed rate. By performing this analysis, it can be decided which independent factor dominates over the other. It can be observed from the Tables 7, 8 and 9 that the drill diameter has the highest influence on the thrust force and roughness, spindle speed has the highest influence on ovality.

Main effect plots of S/N ratios for thrust force, surface roughness and ovality are shown in Figures 19, 20 and 21.

Table-7. S/N ratios for force.

Taguchi Analysis: Force versus Drill dia, Speed, Feed rate

Response Table for Signal to Noise Ratios
Smaller is better

Level	Drill dia	Speed	Feed rate
1	-42.36	-48.00	-45.10
2	-46.78	-45.46	-46.35
3	-49.07	-44.74	-46.75
Delta	6.71	3.26	1.65
Rank	1	2	3

Table-8. S/N ratios for roughness.

Taguchi Analysis: Roughness versus Drill dia, Speed, Feed rate

Response Table for Signal to Noise Ratios
Smaller is better

Level	Drill dia	Speed	Feed rate
1	-14.99	-15.02	-14.65
2	-16.53	-15.33	-14.42
3	-13.80	-14.96	-16.25
Delta	2.73	0.37	1.83
Rank	1	3	2

Table-9. S/N ratios for ovality.

Taguchi Analysis: Ovality versus Drill dia, Speed, Feed rate

Response Table for Signal to Noise Ratios
Smaller is better

Level	Drill dia	Speed	Feed rate
1	1.48866	-2.39409	-4.25000
2	0.06538	-3.40966	0.06328
3	-2.92404	4.43376	2.81672
Delta	4.41270	7.84342	7.06672
Rank	3	1	2

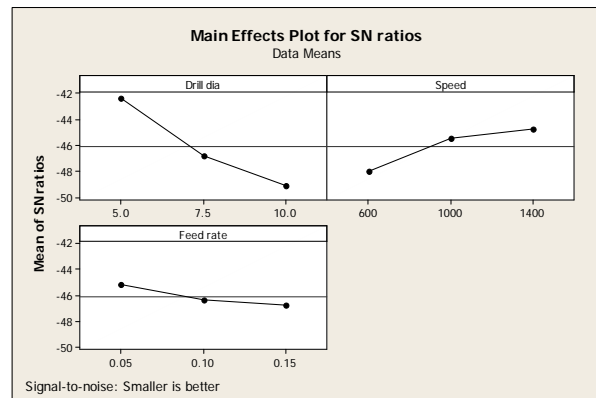


Figure-19. Main effect plots for S/N ratios-force.

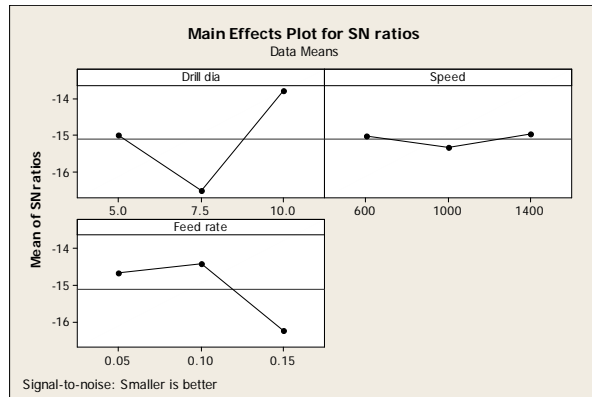


Figure-20. Main effect plots for S/N ratios - roughness.

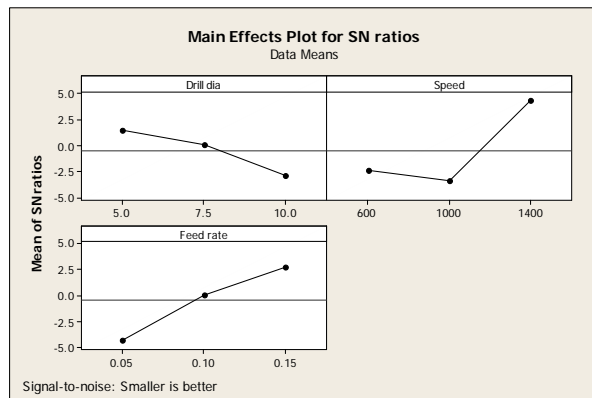


Figure-21. Main effect plots for S/N ratios - ovality.

CONCLUSIONS

Second order response surface models have been developed for correlating various drilling parameters with respect to thrust force, surface roughness and ovality of the drilled holes. The developed models are significant at 95% confidence level, and so they can be effectively used for drilling of Al / SiC metal matrix composites within the range of the process parameters.

Using RSM, different 3D response surfaces are plotted to show the effect of the process parameters on the response of interest.

Analysis of Variance revealed the dominant factors that influence the performance of the drilling process and quality of the drilled hole surfaces like ovality and roughness. From the analysis it was concluded that the drill tool diameter is having high influence on drilling force and feed rate on roughness of the drilled hole surfaces. Spindle speed is having high influence on the percentage ovality of the drilled holes.

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