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Optimization in Machining of Al/SiCp Composites by a Uncoated Solid Carbide Tool using Response Surface Methodology (RSM)

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Abstract : Metal matrix composites have been widely used in industries, especially aerospace industries, due to their excellent engineering properties. However, it is difficult to machine them because of the hardness and abrasive nature of reinforcement elements like silicon carbide particles (SiC_p). In the present study, an attempt has been made to investigate the influence of spindle speed (N), feed rate (f), depth of cut (d) and various % *wt*. of silicon carbide (S) manufactured through stir cast route on tool flank wear, surface roughness and metal removal rate during end milling of LM 25 Al/SiC_p metal matrix composites. Experiments were carried out according to response surface methodology (RSM). Mathematical models were developed for the tool flank wear and surface roughness. Graphs were drawn to study the effect of process parameters as well as their interactions. The process parameters are optimized using desirability-based approach response surface methodology.

Keywords : *Metal matrix composites (MMC), Response surface methodology (RSM), Tool flank wear (VB_{max}), Surface roughness (Ra) and Metal removal rate (MRR).*

1. INTRODUCTION

Metal matrix composites (MMC) are the new class of materials and are being used to replace conventional materials in various engineering applications such as the aerospace and automobile industries. The most popular reinforcements are silicon carbide (SiC) and alumina (Al2O3). Aluminum, titanium, and magnesium alloys are commonly used as the matrix phase. The density of most of the MMCs is approximately one third that of steel, resulting in high-specific strength and stiffness [1]. In the last decades, SiC/Al composites have been increasingly used in the aerospace industry and advanced arm systems such as satellite bearing, inertia navigation system, and laser reflector. Particulate metal matrix composites (PMMCs) are most commonly manufactured by a stir-casting technique or powder metallurgy technique [2].

Several studies have been done in order to examine the efficiency of different cutting tool materials, such as carbide, coated carbide, and diamond in turning, milling, drilling, reaming, and threading of MMC materials. The main problem while machining MMC is the extensive tool wear caused by the very hard and abrasive reinforcements. Manna et al. [3] investigated the machinability of Al/SiC MMC and found that no built-up edge

(BUE) is formed during machining of Al/SiC MMC at high speed and low depth of cut and also observed a better surface finish at high speed with low feed rate and low depth of cut. Davim et al. [4] made a correlation between the chip compression ratio and shear plane angle or chip deformation during MMCs turning. The results showed shear angle decreased with the chip compression ratio.

Kannan et al. [5] studied tool wear, surface integrity, and chip formation during machining of Al-MMC under both wet and dry condition. The turning results showed that the tool life was increased at higher cutting speeds in influence of coolant but the surface quality was deteriorated. Tamer Ozben et al. [6] investigated the mechanical properties and the effects of machining parameters on tool wear and surface roughness of silicon carbide particulate (SiCp) reinforced aluminum MMC for different volume fraction. It was observed that the increase in reinforcement addition produced better mechanical properties higher tool wear. The surface roughness was generally affected by feed rate and cutting speed.

Palanikumar [7] developed a model for surface roughness through response surface method (RSM) while machining GFRP composites. Four factors five level central composite rotatable design matrix was employed to carry out the experimental investigation.

From the literature it is found that the machining of Al MMC is an important area of research, but only very few studies have been carried out on optimization of tool flank wear, surface roughness and metal removal rate while machining of particulate aluminum metal matrix composite (PAMMC). Hence, the main objective of the present work is to optimize the parameter with a view to minimizing surface roughness, minimizing tool flank wear and maximizing MRR. The method presented here may be useful in a machine and/or manufacturing shop.

2. EXPERIMENTAL PLANNING

In the present experimental study, the material to be machined is LM25 Al alloy reinforced with SiC_p with various percentage weight and of 25 μm particle size. The dimensions of the specimens were of 100 mm × 50 mm × 40 mm.

Table 1
Chemical composition of LM25 aluminum alloy (% *wt*)

Material	*Si*	*Mg*	*Mn*	*Fe*	*Cu*	*Ni*	*Ti*
LM25 Al alloy	7	0.33	0.3	0.5	0.1	0.1	0.2

The chemical composition of the LM25 Al alloy specimen is presented in Table 1. The cutting tools used were flat end uncoated solid carbide cutters, having diameter of 12 mm, helix angle of 45º, rake angle of 10º and number of flutes 4. The experiments were planned using central composite design (CCD). Three cutting parameters were selected: (1) spindle speed (2) Feed rate (3) depth of cut and (4) Various percentage content of SiCp. Machining parameters used and their levels are presented in Table 2.

Table 2
Experimental parameters and their levels

Factor	*Unit*	*Notation*	*Levels*				
			(–2)	*(–1)*	*0*	*(+1)*	*(+2)*
Spindle speed	RPM	N	2000	2500	3000	3500	4000
Feed rate	mm/rev	f	0.02	0.03	0.04	0.05	0.06
Depth of cut	mm	d	0.5	1	1.5	2	2.5
Silicon Carbide	%wt	S	5	10	15	20	25

The machining operations were carried out as per the conditions given by the design matrix at random to avoid systematic errors. The tool flank wear (VB_{max}) was measured by using Metzer tool maker's microscope. The surface roughness (Ra) of the machined test specimens was measured using a Talysurf tester with a sampling length of 10mm. Metal removal rate Metal removal rate is one of the most important criteria determining the machining operation, with a higher rate always preferred in such operations. The metal removal rate in mm^3/min has been calculated using the following expression.

$$\text{Metal Removal rate (MRR)} = N \times f \times d \times D \quad mm^3/min \tag{1}$$

where N = spindle speed in RPM ;

f = feed in mm/rev;

d = depth of cut in mm;

D = diameter of the solid end mill cutter in mm.

3. DESIGN OF EXPERIMENT BASED ON RESPONSE SURFACE METHODOLOGY

In order to investigate the influence of process parameters on the tool flank wear, surface roughness and metal removal rate, four principal process parameters such as the spindle speed (N), feed rate (*f*), depth of cut (*d*), and percentage weight of silicon carbide (S) were taken. In this study, these process parameters were chosen as the independent input variables. The desired responses are the tool flank wear, surface roughness and metal removal rate which are assumed to be affected by the above four principal process parameters.

Table 3
Experimental Design Matrix and Results

Exp. No.	*Coded factors*				*Actual factors*				*Flank wear, VB_{max} (mm)*	*Surface roughness, Ra (µm)*	*Metal removal rate, (mm^3/min)*
	X_1	X_2	X_3	X_4	*N*	*f*	*d*	*S*			
1.	-1	-1	-1	-1	2500	0.03	1	10	0.224	4.406	900
2.	1	-1	-1	-1	3500	0.03	1	10	0.284	3.812	1260
3.	-1	1	-1	-1	2500	0.05	1	10	0.258	6.034	1500
4.	1	1	-1	-1	3500	0.05	1	10	0.291	5.229	2100
5.	-1	-1	1	-1	2500	0.03	2	10	0.235	4.472	1800
6.	1	-1	1	-1	3500	0.03	2	10	0.294	3.802	2520
7.	-1	1	1	-1	2500	0.05	2	10	0.27	6.032	3000
8.	1	1	1	-1	3500	0.05	2	10	0.297	5.312	4200
9.	-1	-1	-1	1	2500	0.03	1	20	0.338	4.978	900
10.	1	-1	-1	1	3500	0.03	1	20	0.407	4.395	1260
11.	-1	1	-1	1	2500	0.05	1	20	0.377	6.789	1500
12.	1	1	-1	1	3500	0.05	1	20	0.422	5.945	2100
13.	-1	-1	1	1	2500	0.03	2	20	0.358	5.071	1800
14.	1	-1	1	1	3500	0.03	2	20	0.413	4.402	2520
15.	-1	1	1	1	2500	0.05	2	20	0.384	6.804	3000

Exp. No.	*Coded factors*				*Actual factors*				*Flank wear, VB_{max} (mm)*	*Surface roughness, Ra (µm)*	*Metal removal rate, (mm³/min)*
	X_1	*X_2*	*X_3*	*X_4*	*N*	*f*	*d*	*S*			
16.	1	1	1	1	3500	0.05	2	20	0.419	6.054	4200
17.	-2	0	0	0	2000	0.04	1.5	15	0.262	6.202	1440
18.	2	0	0	0	4000	0.04	1.5	15	0.361	4.638	2880
19.	0	-2	0	0	3000	0.02	1.5	15	0.314	3.679	1080
20.	0	2	0	0	3000	0.06	1.5	15	0.357	7.008	3240
21.	0	0	-2	0	3000	0.04	0.5	15	0.309	5.062	720
22.	0	0	2	0	3000	0.04	2.5	15	0.341	5.299	3600
23.	0	0	0	-2	3000	0.04	1.5	5	0.211	4.334	2160
24.	0	0	0	2	3000	0.04	1.5	25	0.443	5.639	2160
25.	0	0	0	0	3000	0.04	1.5	15	0.322	5.183	2160
26.	0	0	0	0	3000	0.04	1.5	15	0.328	5.177	2160
27.	0	0	0	0	3000	0.04	1.5	15	0.319	5.221	2160
28.	0	0	0	0	3000	0.04	1.5	15	0.326	5.163	2160
29.	0	0	0	0	3000	0.04	1.5	15	0.323	5.155	2160
30.	0	0	0	0	3000	0.04	1.5	15	0.327	5.199	2160
31.	0	0	0	0	3000	0.04	1.5	15	0.329	5.229	2160

The response surface methodology is employed for modeling and analyzing the process parameters in the end milling process so as to obtain the machinability performances of VB_{max}, Ra and MRR. In the RSM, the quantitative form of relationship between the desired response and independent input variables are represented as follows:

$$Y = F\{N, f, d, S\} \tag{2}$$

Where Y is the desired response and F is the response function (or response surface). In the procedure of analysis, the approximation of Y was proposed using the fitted second-order polynomial regression model, which is called the quadratic model. The quadratic model of Y can be written as follows:

$$Y = a_0 + \Sigma a_i X_i + \Sigma a_{ii} X_i^2 + \Sigma a_{ij} X_i X_j \tag{3}$$

Where a_0 is constant, a_i, a_{ii}, and a_{ij} represent the coefficients of linear, quadratic, and cross product terms, respectively. X_i reveals the coded variables that correspond to the studied machining parameters. The coded variables X_i, $i = 1, 2, 3, 4$ are obtained from the following transformation equations:

$$X_1 = [N - N_0] / \Delta N \tag{4}$$

$$X_2 = [f - f_0] / \Delta f \tag{5}$$

$$X_3 = [d - d_0] / \Delta d \tag{6}$$

$$X_4 = [S - S_0] / \Delta S \tag{7}$$

where X_1, X_2, X_3, and X_4 are the coded values of parameters N, *f*, *d*, and S respectively; N_0, f_0, d_0, and S_0 are the values of N, *f*, *d*, and S, respectively, at zero level. ΔN, Δ*f*, Δ*d*, and ΔS are the intervals of variation in N, *f*, *d*, and S, respectively. The purpose of using this quadratic model Y in this study was not only to investigate over the entire factor space but also to locate the region where the response approaches its optimum or near optimal value of the desired target. The necessary data for building the response models are generally collected by the experimental design.

The pertinent process parameter selected for the present investigation are spindle speed, feed rate, depth of cut and percentage weight of silicon carbide on the tool flank wear, surface roughness and metal removal rate during the end milling process. For the four variables the design required 31 experiments with 16 factorial points, eight axial points to form central composite design with α = 2 and seven center points for replication to estimate the experimental error. The design was generated and analyzed using MINITAB 15.0 statistical package. The levels of each factor were chosen as −2, −1, 0, 1, 2 in closed form to have a rotatable design [8]. Table 2 shows the factors and their levels in coded and actual values. The experiment has been carried out according to the designed experimentation based on central composite second-order rotatable design as depicted in Table 3.

4. MATHEMATICAL MODELING

Mathematical models based on second-order polynomial equations were developed for tool flank wear and surface roughness using the experimental results shown in Table 3 and are given below:

$$VB_{max} = -0.2551 + (0.0002\,X_1) + (2.4923\,X_2) + (0.0404\,X_3) + (0.0084\,X_4) + (34.4196\,X_2^2) + (0.0033\,X_3^2) + (0.0001\,X_4^2) - (0.0013\,X_1 X_2) - (0.3125\,X_2 X_3) + (0.0088\,X_2 X_4) - (0.0002\,X_3 X_4) \quad (8)$$

$$Ra = 4.716 - (0.002\,X_1) + (61.948\,X_2) + (0.050\,X_3) + (0.099\,X_4) + (365.551\,X_2^2) - (0.017\,X_3^2) - (0.002\,X_4^2) - (0.008\,X_1 X_2) + (0.612\,X_2 X_3) + (0.789\,X_2 X_4) + (0.002\,X_3 X_4) \quad (9)$$

Where X_1, X_2, X_3, and X_4 represent the decoded values of spindle speed (N), feed rate (*f*), depth of cut (*d*), and percentage weight of silicon carbide (S), respectively. The metal removal rate has been calculated using the Eq. 1.

5. RESULTS AND DISCUSSION

5.1. Effect of machining parameters on tool flank wear (VB_{max})

Based on the mathematical model given by Eq. 8 developed through experimental observations and response surface methodology, studies have been made to analyze the effect of the various process parameters on the flank wear (VB_{max}). Figure 1, 2 shows the effect for two varying parameters by keeping the third and fourth variable at middle level. Fig. 1 shows the effects of spindle speed at different percentage weight of SiC_p on flank wear. With a fixed value of spindle speed the flank wear increases with the increase in percentage weight of SiC_p. From the figure, it can be concluded that the low spindle speed and low percentage weight of SiC_p are preferred for machining of Al/SiC_p MMC. Fig. 2 shows the effects of feed rate at different percentage weight of SiC_p on flank wear. With a fixed value of feed rate the flank wear increases with the increase in percentage weight of SiC_p. From the figure, it can be concluded that the low feed rate and low percentage weight of SiC_p are preferred for machining of Al/SiC_p MMC.

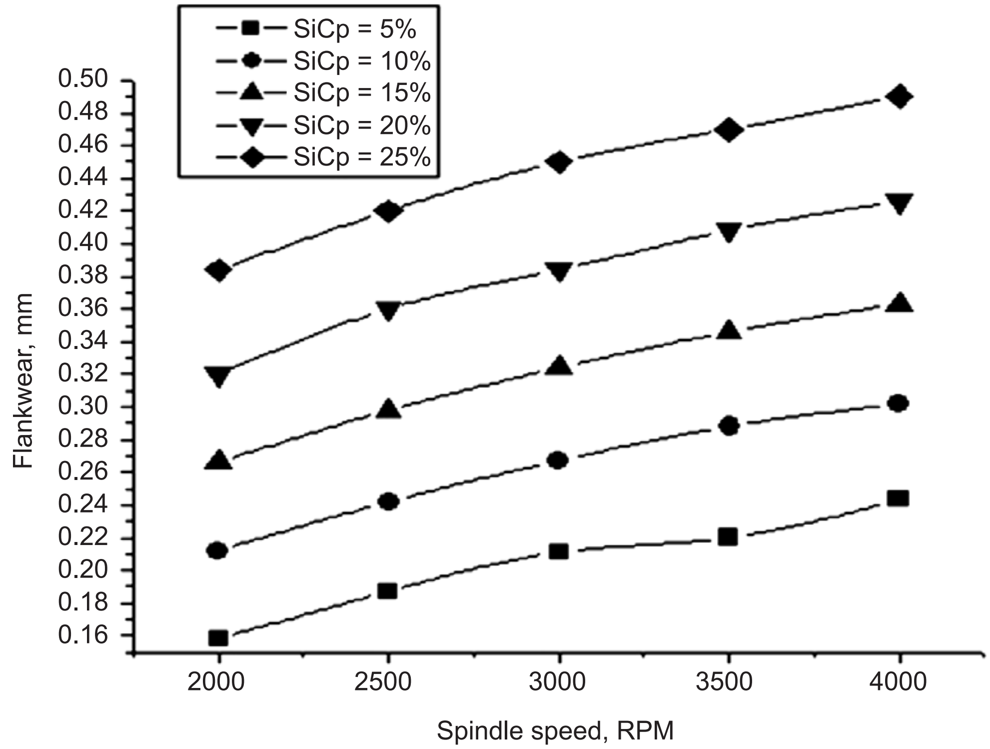

Figure 1: Effect of spindle speed at different %wt. of SiC_p on VB_{max}

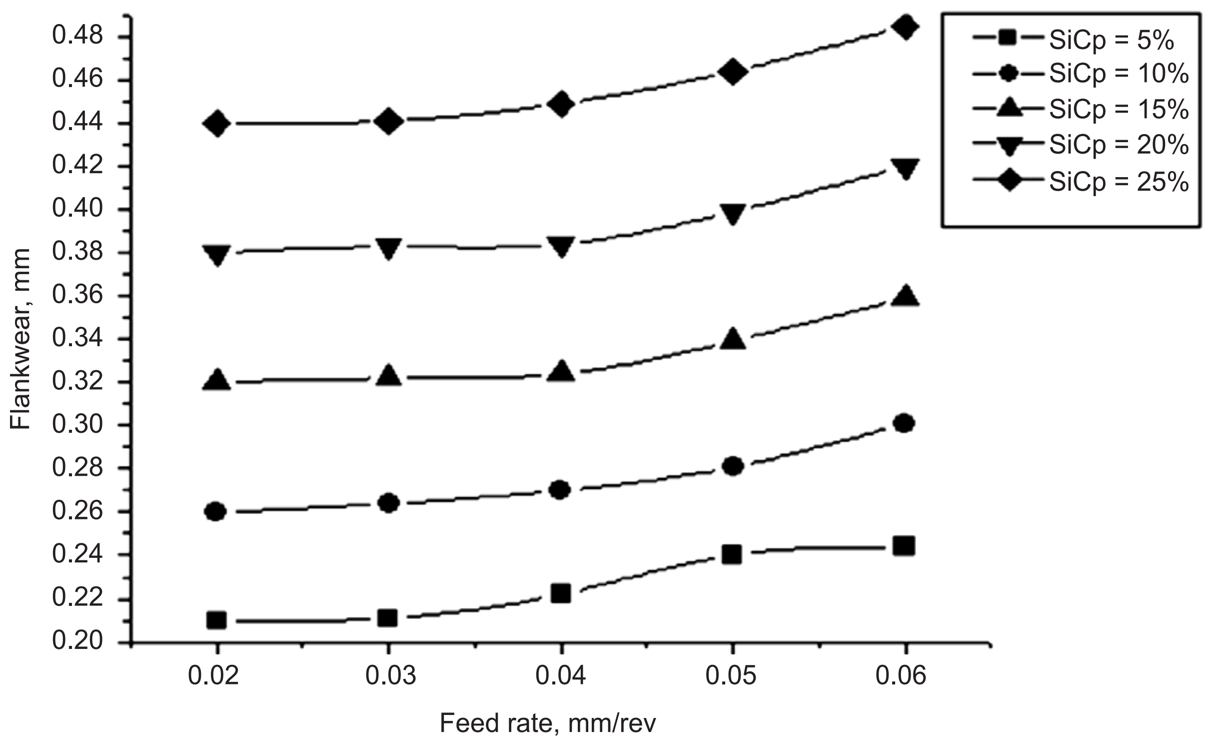

Figure 2: Effect of feed rate at different %wt. of SiC_p on VB_{max}

5.2. Effect of machining parameters on surface roughness (Ra)

Based on the mathematical model given by Eq. 9, the study of the effects of various process parameters on surface roughness (Ra) has been made so as to analyze the suitable parametric combinations that can be made for achieving controlled surface roughness. Figure 3, 4 shows the effect for two varying parameters by keeping the third and fourth variable at middle level. Fig. 3 shows the effects of spindle speed at different feed rate on the surface roughness. With a fixed value of feed rate the surface roughness reduces with the increase of spindle speed. From the figure, it can be concluded that the high spindle speed and low feed rate are preferred for machining of Al/SiC_p MMC. Fig. 4 shows the effects of feed rate at different percentage weight of SiC_p on surface roughness. With a fixed value of feed rate the surface roughness increases with the increase in percentage weight of SiC_p. From the figure, it can be concluded that the low feed rate and low percentage weight of SiC_p are preferred for machining of Al/SiC_p MMC.

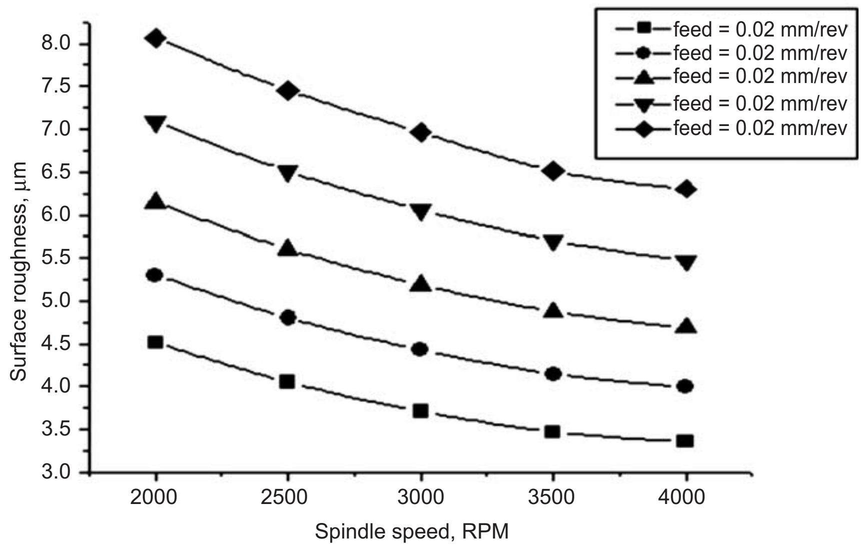

Figure 3: Effect of spindle speed at different feed rate on Ra

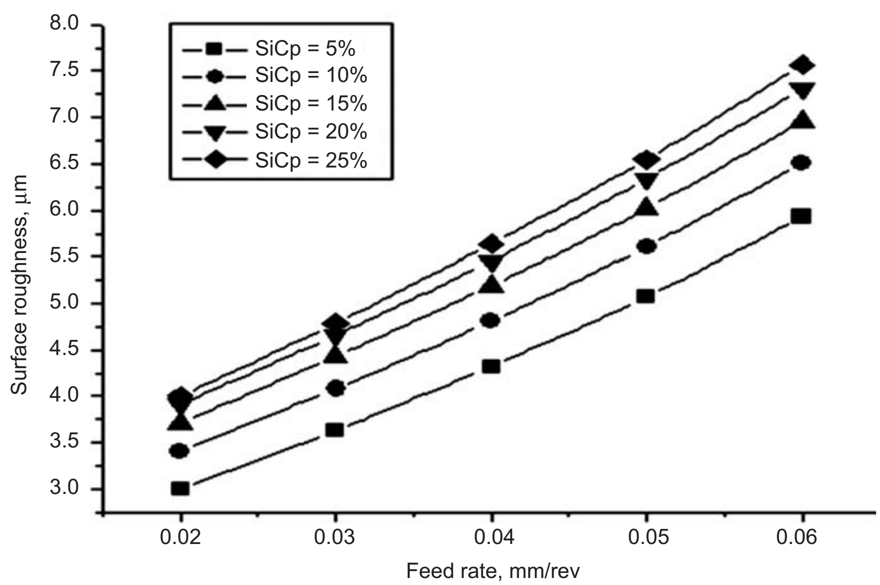

Figure 4: Effect of feed rate at different %wt. of SiC_p on Ra

6. ANALYSIS FOR OPTIMIZATION OF THE RESPONSES

After building the regression model, a numerical optimization technique using desirability functions can be used to optimize the response. The objective of optimization is to find the best settings that minimize a particular response. A desirability value, where $0 \leq d \leq 1$. The value of d increases as the "desirability" of the corresponding response increases. The factor settings with maximum desirability are considered to be the optimal parameter conditions. Most of the standard statistical software packages (Minitab, Design, Expert, etc.) employ.

This popular technique for response optimization. In the present case, Minitab was used to optimize the response parameters.

The optimization plot for tool flank wear, surface roughness and metal removal rate is shown in Fig.5. The objective is to minimize (VB_{max} and Ra) and maximize the (MRR) responses considered at a time. As the composite desirability is close to 1, it can be concluded that the parameters are within their working range. The optimized values of process parameters are spindle speed (N) 3201.7094 RPM, feed rate (f) 0.0242 mm/rev, depth of cut (d) 2.5 mm, and %wt. of silicon carbide (S) 5. Machining with optimum parametric combination, tool wear (VB_{max}) can be achieved as low as 0.2367mm, surface roughness (Ra) can be achieved as low as 3.1585 mm and metal removal rate (MRR) can be achieved as high as 2363.1653 mm^3/min.

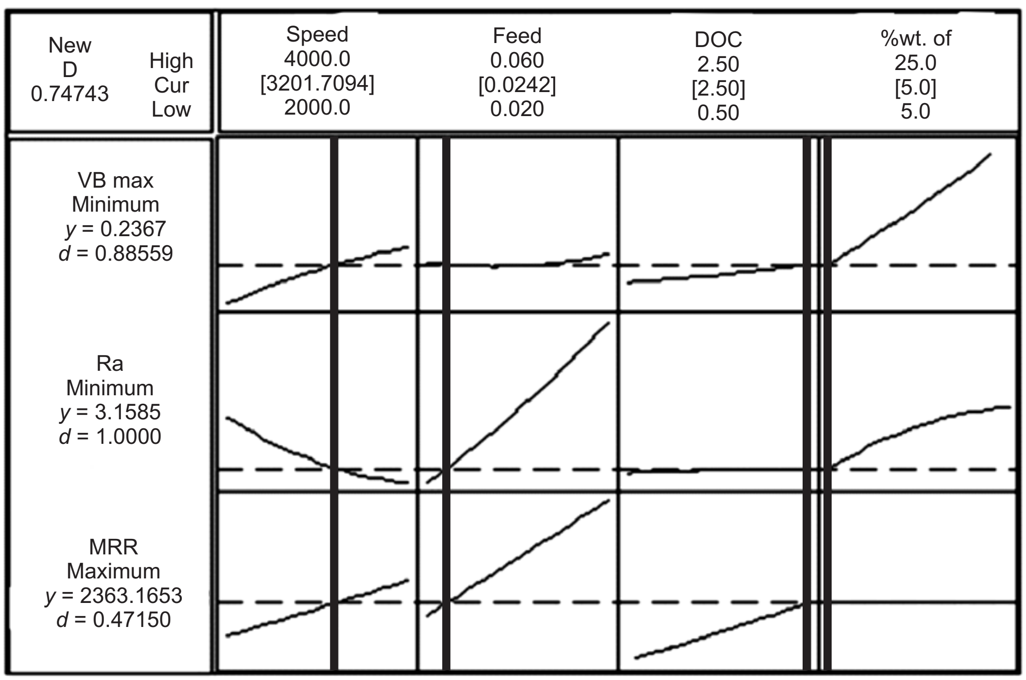

Figure 5: Optimization plot of $VB_{max,}$ Ra and MRR

7. CONCLUSIONS

The experimental analysis highlights that the machining criteria like VB_{max}, Ra and MRR in composite machining are greatly influenced by the various predominant process parameters considered in the present study. The second-order polynomial models were developed for tool flank wear and surface roughness, and were used for optimization. The metal removal rate was calculated using a theoretical equation.

Formation of BUE significantly affects the tool wear at low spindle speed whereas thermal softening plays important role at higher spindle speed, and feed rate. The tool wear is low at lower spindle speed, low percentage weight of silicon carbide, lower feed rate ranges and low depth of cut.

The surface roughness is significantly affected by BUE formation at low spindle speed. The surface roughness is low at higher spindle speed, lower feed rate ranges and low percentage weight of silicon carbide. Depth of cut has less influence on surface roughness.

Metal removal rate is one of the most important criteria determining the machining operations. Metal removal rate has been calculated using equation 1.

The optimization plots were drawn for tool flank wear, surface roughness and metal removal rate. The emphasis is to provide the process engineer a preferred solution in a short period of time.

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