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An experimental study of effect of process parameters in turning of LM6/SiC$_P$ metal matrix composite and its prediction using response surface methodology

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Abstract

In the present investigation an attempt is made to evaluate the effect of certain cutting variables on surface roughness in plain turning of aluminium alloy (LM6) - SiCp metal matrix composites under dry cutting condition. Cutting velocity, depth of cut and weight percentage of SiC$_P$ in the metal matrix are selected as the influencing parameters. The experiments are conducted based on three factors, two level and central composite face centered design (CCD) with full factorial and the results are analyzed according to the principle of Response Surface Methodology. The equation to the response surface is developed using the design of experiments features of the commercial software package MINITAB-14. The goodness of fit of the regression model is examined using the Analysis of Variance (ANOVA) and the F-ratio test. The contour plots of the process parameters revel that the best surface finish is associated with the lowest level of depth of cut, the lowest level of the weight percentage of SiCp in the metal matrix and the highest level of cutting velocity. These conclusions are further verified through eight confirmatory experiments and with the help of the sensitivity analysis.

Keywords: Metal Matrix Composites, Response Surface Methodology, Surface Roughness, ANOVA.

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1. Introduction

In recent years research in aluminium metal matrix composites has been receiving growing attention from investigators because of their increasing applications in aerospace, automobile and mineral processing industries (Lindroos and Talvite, 1995; Brown *et al.*, 1995). This is because of their superior mechanical properties such as high (strength/weight) ratio and high thermal conductivity. These composites are manufactured by introducing hard ceramic reinforcements such as zirconia, alumina and silicon carbide (SiC) into the aluminium base matrix in the form of particulates, fibres or whiskers (Christophe *et al.*, 1996).. These particles when uniformly distributed in the matrix increase its strength, stiffness, resistance to wear, corrosion and fatigue and elevated temperature characteristics of the matrix. Among these reinforcements SiC is found to be chemically compatible with aluminium forming a sufficiently strong bond with the matrix without developing a inter-metallic phase. Further, addition of SiCp improves the thermal conductivity of the base metal and its workability (Nair *et al.*, 1985).

There are several methods of manufacture of MMCs. Of these, the stir casting method is very popular due to its unique advantages (Hashim *et al*,1999; Kaczmar *et al* 2000; Sleziona 1994,1995). In this method the reinforcing particles are introduced into the melt and are stirred thoroughly to ensure their homogeneous mixing with the matrix alloy. The properties of the particle reinforced metal matrix composites produced this way are influenced to a large extent by the type, size and weight fraction of the reinforcing particles and their distribution in the cast matrix.

An enduring problem with MMCs is that they are difficult to machine. This is due to the high hardness of the reinforcement materials which in many cases are significantly harder than the commonly used high speed steel tools and carbide tools. This results in rapid tool wear and poor quality of the machined surface making the machining of these composites very costly. These attributes impede their application as common engineering materials.

Machinability studies of metal matrix composites have received the attention in the past of a number of investigators. These studies have mostly focused on optimizing some machining parameters so that an output variable such as surface roughness or tool wear is minimized the experimental data being analyzed using some statistical technique for design of experiments(DoE). Thus, Muthu-Krishnan [2008 a,b] applied ANOVA and ANN for the optimization of the machining parameters in plain turning of Al-SiC composites. The Response Surface Methodology (RSM) and Taguchi's method were applied by Shetty (2009) and Davim (2002) to establish optimum cutting conditions (cutting speed, feed rate and depth of cut) in turning of reinforced aluminium composites so that roughness of the machined surface and tool wear are minimized. Application of Design of Experiment techniques to surface grinding and end milling is also reported in literature (Arokiadass *et al*., 2011; Pai *et al*, 2011).

In the present investigation an attempt is made to study the effect of some cutting variables on surface roughness in plain turning of LM6 Al/SiC$_p$ (MMC) under dry cutting condition using Response Surface Methodology. Cutting speed, depth of cut and weight percentage of SiC in the metal matrix were chosen as the influencing parameters and a 2^3 full factorial design of experiments was carried out to collect the experimental data and to analyze the effect of these parameters on surface roughness. A second order model is established between the independent parameters and the surface roughness using RSM. The analysis shows excellent agreement between the predicted and the experimental values.

2. Experimental Procedure

Fabrication of MMCs

The discontinuous MMCs used in this study were prepared following the stir casting route. The matrix closely confirmed to the LM6 aluminium alloy and the reinforcement was silicon carbide (SiC) particulates. The composition of LM6 is tabulated in Table 1.

Table 1: Chemical Composition (LM6)

Elements	Si	Cu	Mg	Fe	Mn	Ni	Zn	Pb	Sb	Ti	Al
Percentage (%)	10-13	0.1	0.1	0.6	0.5	0.1	0.1	0.1	0.05	0.2	Remaining

To prepare the specimens the aluminum alloy was melted in an electric resistance furnace having a clay graphite crucible. The melt was mechanically stirred by an impeller after addition of pre-heated silicon carbide particles (pre heat temperature=900^{0}C average particle size =37µm). The processing of the composite was carried out at a temperature of 750^{0}C with a stirring speed of 500 rpm. The melt was poured at a temperature of 745^{0}C into sand mold. The dimension of the work piece was cylindrical (35 mm diameter and 90 mm length).

Plan of Experimentation

The turning experiments were conducted according to Response Surface Methodology that required 20 runs and 19 degrees of freedom corresponding to three levels of parameters. The parameters selected for experimentation were cutting speed (V), depth of cut (D) and wt% of SiC$_P$ (S). The parameters and their levels are presented in Table 2.

Table 2. Experimental parameter and their level

Parameters	Unit	Symbol	Level		
			-1	0	+1
Cutting speed	m/min	V	30	60	90
Depth of cut	mm	D	0.5	1.0	1.5
Silicon carbide	wt%	S	7.5	10.0	12.5

The turning operation was carried out on a medium duty lathe of spindle power 2.5 KW. using a cutting tool of Polycrystalline diamond (PCD). The machining length was approximately 60mm. The surface roughness was measured using a Mitutoyo surf test (Make-Japan –Model SJ-301) at three different locations along the machined length and the mean of these three readings was used for the purpose of analysis.

3. Mathematical Modeling

Response Surface Methodology

Response Surface Methodology (RSM) adopts both mathematical and statistical techniques which are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables. The independent variables x_1, x_2 …. x_k are presumed to be continuous that can be controlled with negligible error. The response $\overline{H}$ is postulated to be a random variable. In most experimental conditions, it is possible to represent the independent factors in quantitative form which have a functional relationship with response $\overline{H}$. This may be written as (Montgomery, 1991):

$$\overline{H} = f(x_1, x_2, ...) \pm \varepsilon \tag{1}$$

Where ε measures the experimental error (noise).

In Response Surface Methodology 'f' is represented by a second order polynomial in independent variables Xs. This is given by Montgomery (1991):

$$\overline{H} = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i}^{k} \sum_{j}^{k} \beta_{ij(i<j)} x_i x_j + \varepsilon \tag{2}$$

For three variables, the above polynomial reduces to

$$R_a = \beta_0 + \beta_1 V + \beta_2 D + \beta_3 S + \beta_{11} V^2 + \beta_{22} D^2 + \beta_{33} S^2 + \beta_{12} VD + \beta_{13} VS + \beta_{23} DS \tag{3}$$

Table 3 Design of Experiment and Response Results

	Coded Value			Real Value			Surface Roughness
Std.	V	D	S	Cutting Speed (m/min)	Depth of Cut (mm)	SiCp (wt %)	(Ra) (μm)
1	-1	-1	-1	30.0	0.50	7.50	2.92
2	1	-1	-1	90.0	0.50	7.50	1.92
3	-1	1	-1	30.0	1.50	7.50	3.38
4	1	1	-1	90.0	1.50	7.50	3.18
5	-1	-1	1	30.0	0.50	12.50	4.08
6	1	-1	1	90.0	0.50	12.50	2.64
7	-1	1	1	30.0	1.50	12.50	4.64
8	1	1	1	90.0	1.50	12.50	4.48
9	-1	0	0	30.0	1.00	10.00	4.09
10	1	0	0	90.0	1.00	10.00	3.4
11	0	-1	0	60.0	0.50	10.00	3.16
12	0	1	0	60.0	1.50	10.00	4.02
13	0	0	-1	60.0	1.00	7.50	3.08
14	0	0	1	60.0	1.00	12.50	4.18
15	0	0	0	60.0	1.00	10.00	3.71
16	0	0	0	60.0	1.00	10.00	3.73
17	0	0	0	60.0	1.00	10.00	3.64
18	0	0	0	60.0	1.00	10.00	3.92
19	0	0	0	60.0	1.00	10.00	3.89
20	0	0	0	60.0	1.00	10.00	3.86

Design of Experiments and Data Collection

The surface roughness was estimated through a series of experiments according to the experimental plan based on central composite face centered (CCF) design, as shown in Table 3, to develop the equation of the response surface. Design of experiment (DoE) features of MINITAB-14 software was utilized that determined the coefficients in the response surface regression model. The values of these coefficients are presented in Table 4. The factorial portion of CCF is a full factorial design with all combinations of the factors at two levels (high, +1 and low, −1) and coded level (0) which is the midpoint between the high and low levels. The final model for surface roughness so developed is expressed as:

$$R_a = 3.792 - 0.349V + 0.498D + 0.554S - 0.039V^2 - 0.195D^2 - 0.155S^2 + 0.26VD - 0.05VS + 0.085DS \quad (4a)$$

Table 4 Regression analysis for Surface Roughness

Term	Coefficient	P- Value
Constant	3.792	0.000
V	-0.349	0.000
D	0.498	0.000
S	0.554	0.000
V^2	-0.039	0.546
D^2	-0.195	0.012
S^2	-0.155	0.035
VD	0.260	0.001
VS	-0.050	0.207
DS	0.085	0.045
	R-Sq = 98.6%	R-Sq(adj) = 97.4%

Referring to table 4 it may be seen that most of the terms in equation (4a) are significant since the p-value associated with these terms are less than 0.05. The terms containing V^2 and VS has a p-value greater than 0.05 indicating that these terms do not significantly affect the surface roughness. If the contributions of these terms are neglected a new response equation may be written as:

$$R_a = 3.7869 - 0.349V + 0.498D + 0.554S - 0.195D^2 - 0.155S^2 + 0.26VD + 0.085DS \quad (4b)$$

4. Result and Discussion

Analysis of the developed mathematical model for surface roughness

The goodness of fit of the above regression model was examined using the analysis of variance (ANOVA) technique and the F-ratio test and these results are presented in Table 4 and Table 5 respectively. Referring to Table 4 it may be seen that R^2 value for response is 98.6% which suggests that the regression model provides a very good relationship between the independent variables and the response (Ra). The associated P-value for the model is also found to be lower than 0.05. This indicates that the predictions from equation (4a) are accurate to within 95% confidence level. The P-values also demonstrate that the linear, quadratic and interaction terms all have significant effect on surface roughness.

In Table 5 the calculated values of F-ratio for lack of fit are compared with the standard values of F-ratio corresponding to their degrees of freedom. The standard percentage point of F distribution for 95% confidence level is 3.02. But the F value (0.59) for lack of fit is smaller than the standard value indicating that the model is adequate. The normal probability plot of residuals as shown in Figure.1 also lies fairly close to a straight line suggesting that the errors are normally distributed and the regression model well fitted with the observed values. Figure 2 further demonstrates an excellent correlation between fitted and observed values (maximum variation between -0.15 to 0.1) indicating that the RSM model developed is significant and adequate.

Table-5 Analysis of variance for Surface Roughness

Source	DOF	Sum of Squares	Adj. Mean Squares	F- Value	P- Value
Regression	9	7.9655	0.8851	80.42	0.000
Linear	3	6.7672	2.2557	204.96	0.000
Square	3	0.5797	0.1932	17.56	0.000
Interaction	3	0.6186	0.2062	18.74	0.000
Residual Error	10	0.1100	0.0110		
Lack-of-Fit	5	0.0409	0.0082	0.59	0.710
Pure Error	5	0.0691	0.0138		
Total	19	8.0755			

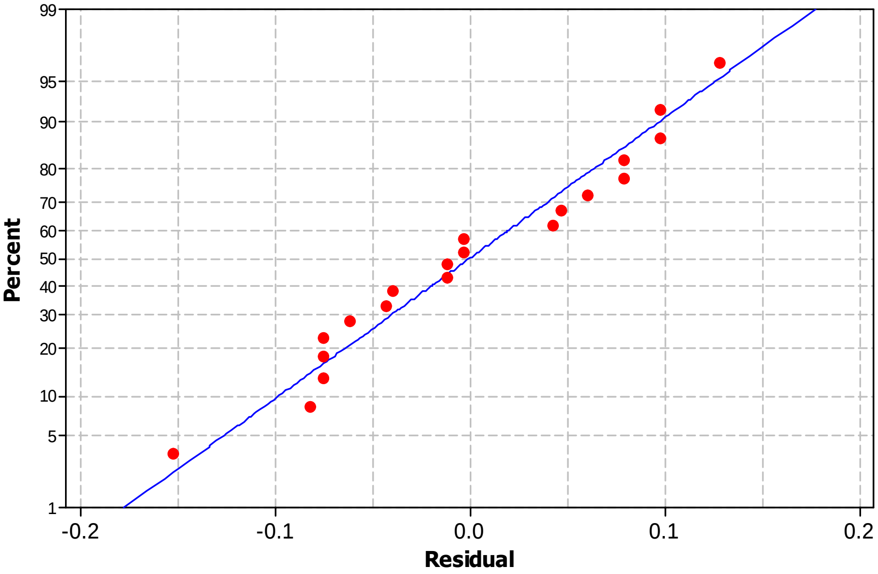

Figure. 1 Normal probability plot of residuals for surface roughness

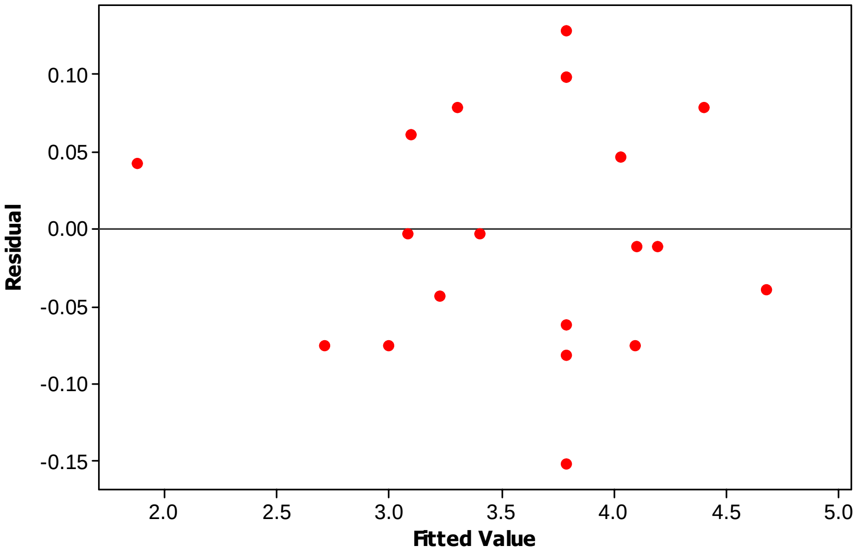

Figure. 2 Plot of residuals vs. the fitted values for surface roughness

Optimizing Parameters

The effects of cutting speed (V), depth of cut (D) and wt% of SiCp (S) on surface roughness (Ra) as predicted by equation (4a) is indicated graphically in figure (3a & 3b), figure (4a & 4b) and figure (5a & 5b) as contour and surface plot. Referring to Figure 3 it may be seen that the surface roughness decreases as cutting speed increases and wt% of SiC_P decrease. For a given value of the cutting speed V, the surface roughness is found to decrease with decrease in depth of cut and wt% of SiCp (Figure 4). Further increasing the cutting speed V and decreasing the depth of cut D is found to improve the surface finish of the machined specimen (Figure 5). Thus the best surface finish is found to be associated with the lowest depth of cut D, the lowest wt% of SiCp and highest cutting speed V. The predicted and the experimental results are found to be very close as may be seen from Figure 6 and Table 6.

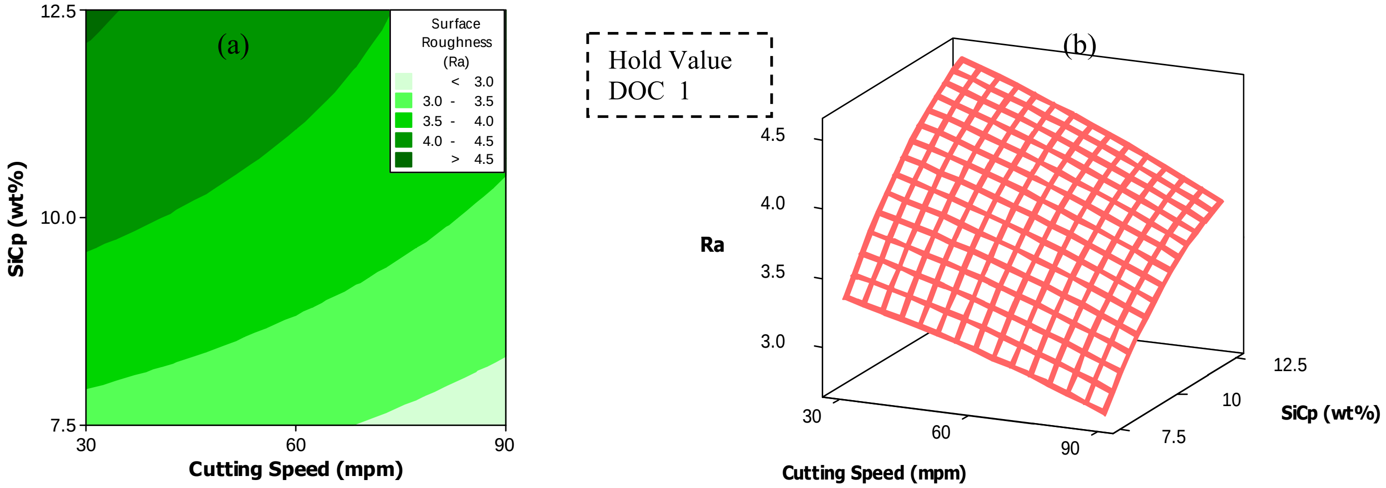

Figure 3. Surface roughness plot for wt% SiCp and cutting speed plane (a) Contour plot (b) Surface plot

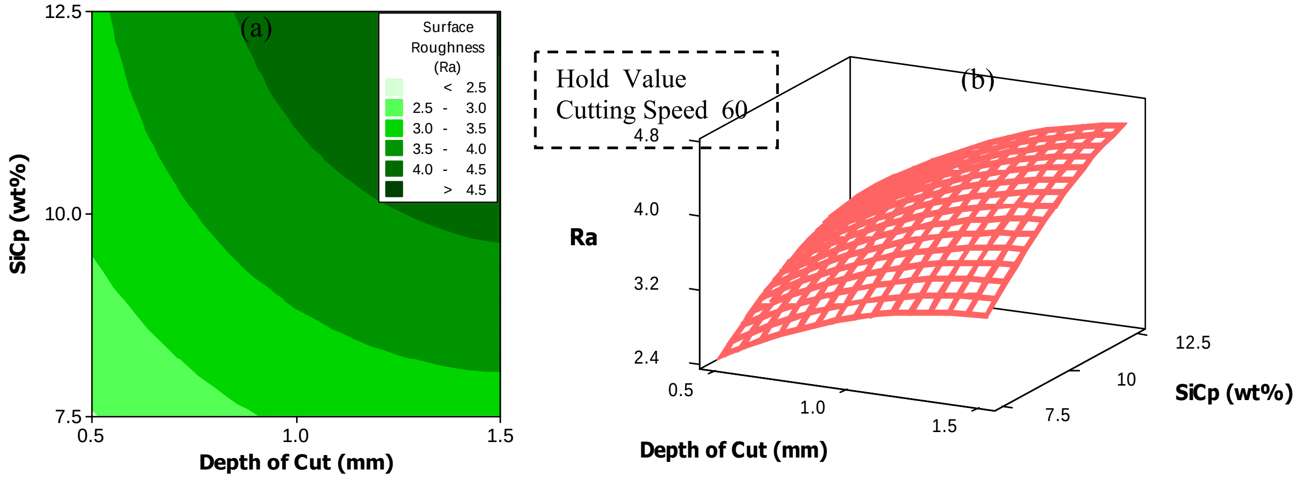

Figure 4. Surface roughness plot for depth of cut and wt% SiCp plane (a) Contour plot (b) Surface plot

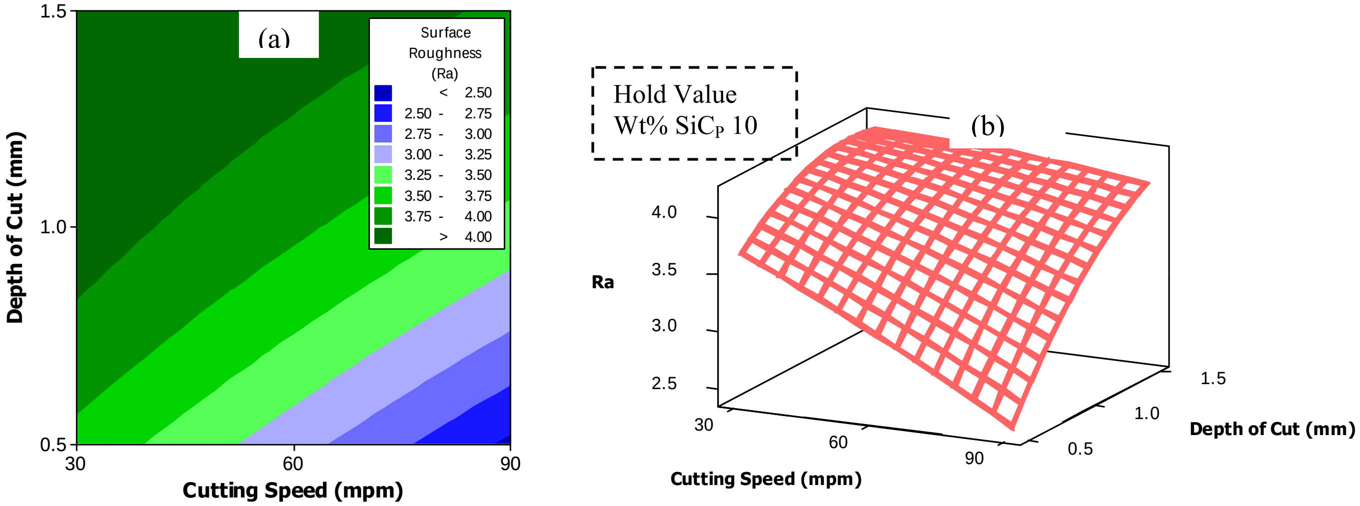

Figure 5. Surface roughness plot for depth of cut and cutting speed plane (a) Contour plot (b) Surface plot

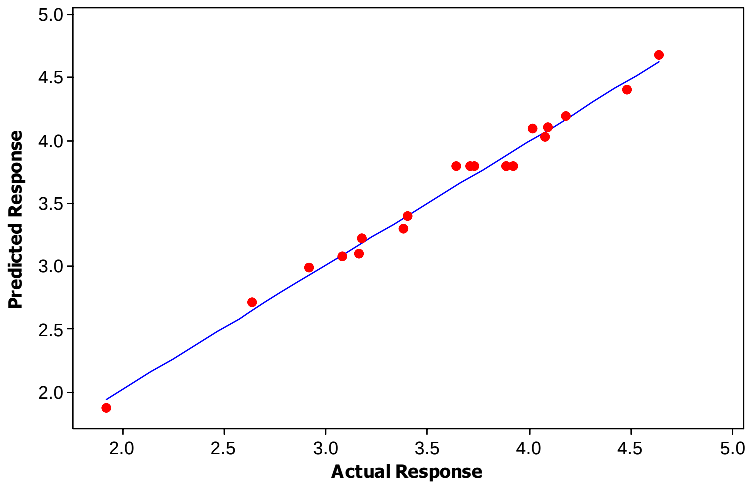

Figure 6. Plot of actual vs predicted response of surface roughness

Table 6 Confirmation experiment

Run	V	D	S	Surface Roughness (Ra)			
				Experiment	Model	Residual	Error (%)
1	30	0.5	7.5	2.92	2.99518	-0.0752	-2.57
2	90	0.5	7.5	1.92	1.87718	0.0428	2.23
3	30	1.5	7.5	3.38	3.30118	0.0788	2.33
4	90	1.5	7.5	3.18	3.22318	-0.0432	-1.36
5	30	0.5	12.5	4.08	4.03318	0.0468	1.14
6	90	0.5	12.5	2.64	2.71518	-0.0751	-2.84
7	30	1.5	12.5	4.64	4.67918	-0.0391	-0.84
8	90	1.5	12.5	4.48	4.40118	0.0788	1.75

5. Sensitivity Analysis

Sensitivity analysis is the first and the most important step in the optimization problems because it yields information about the increment or decrement tendency of the objective function with the design parameter. This method identifies critical parameters and ranks them by their order of importance [Sangϋl *et al*, 2004]. Mathematically, sensitivity of a design objective function with respect to a design variable is the partial derivative of that function with respect to its variables.

To obtain the sensitivity equation for cutting velocity in equation (4a) is differentiated with respect to cutting velocity. The sensitivity equations (5), (6), (7) represent the sensitivity of surface roughness for cutting velocity, depth of cut and wt% of SiCp respectively.

$$\frac{\partial R_a}{\partial V} = -0.349 - 0.078V + 0.26D - 0.05S \tag{5}$$

$$\frac{\partial R_a}{\partial D} = 0.498 - 0.39D + 0.26V + 0.085S \tag{6}$$

$$\frac{\partial R_a}{\partial S} = 0.554 - 0.31S - 0.05V + 0.085D \tag{7}$$

In this study, it is aimed to predict the tendency of surface roughness due to change in process parameters for machining. A positive sensitivity value implies an increment in the objective function due to an increase in design parameters whereas a negative value states the opposite. Sensitivity of surface roughness to cutting velocity, depth of cut and wt% of SiCp as calculated from equations (5), (6) and (7) are shown in Table 7 and Figures (7), (8), (9) respectively. Figure 7 indicates that as cutting velocity increases surface roughness decreases. On the other hand increase in depth of cut or wt% of SiC_P increases surface roughness increases (Figure 8 and Figure 9). The results reveal that the surface roughness is more sensitive to cutting speed than to depth of cut or wt% of SiC_P.

Table 7 Surface Roughness sensitivities of processes parameters (S = 10 wt%)

		Sensitivity		
Depth of cut (mm)	Cutting velocity (m/min)	$\frac{\partial R_a}{\partial V}$	$\frac{\partial R_a}{\partial D}$	$\frac{\partial R_a}{\partial S}$
0.5	30	-0.531	0.628	0.519
	60	-0.609	0.888	0.639
	90	-0.687	1.148	0.419
1.0	30	-0.271	0.238	0.604
	60	-0.349	0.498	0.554
	90	-0.427	0.758	0.504
1.5	30	-0.011	-0.152	0.689
	60	-0.089	0.108	0.639
	90	-0.167	0.368	0.589

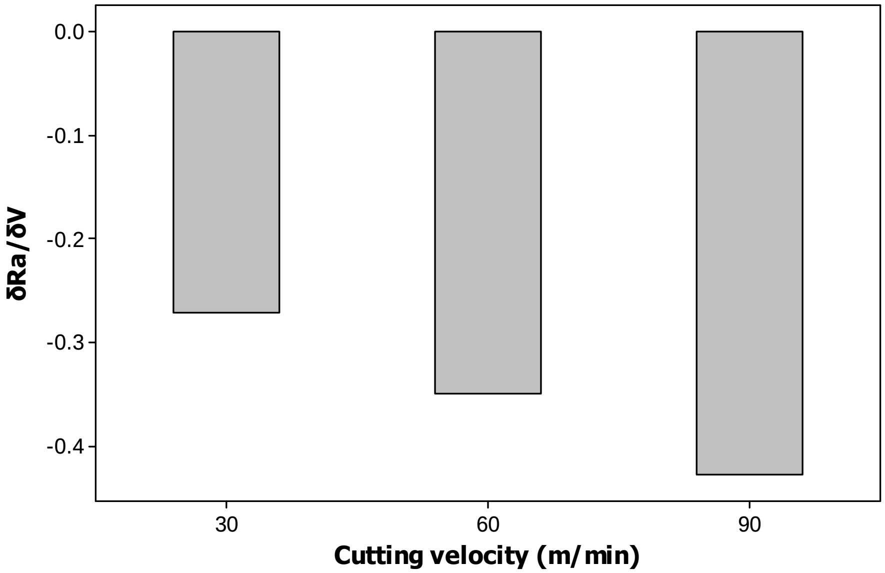

Figure 7. Sensitivity analysis result of cutting velocity

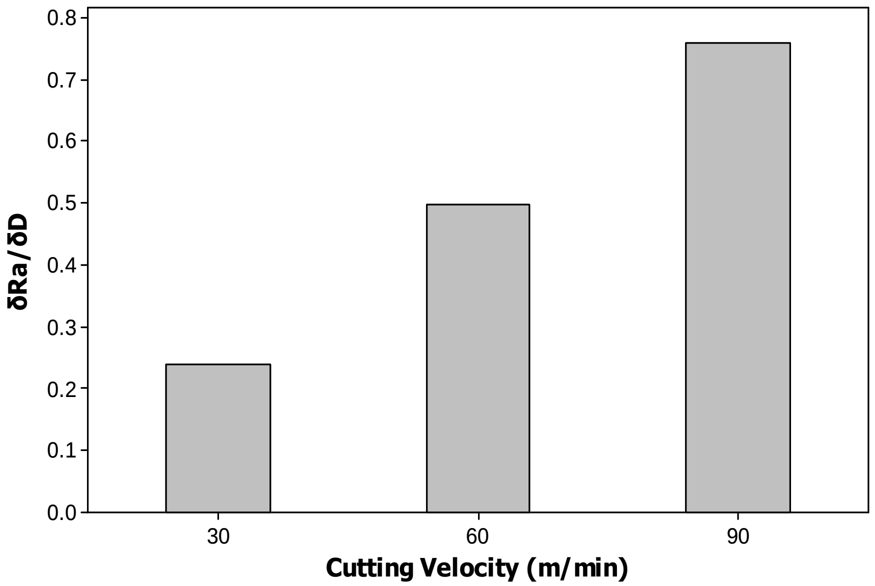

Figure 8. Sensitivity analysis result of depth of cut

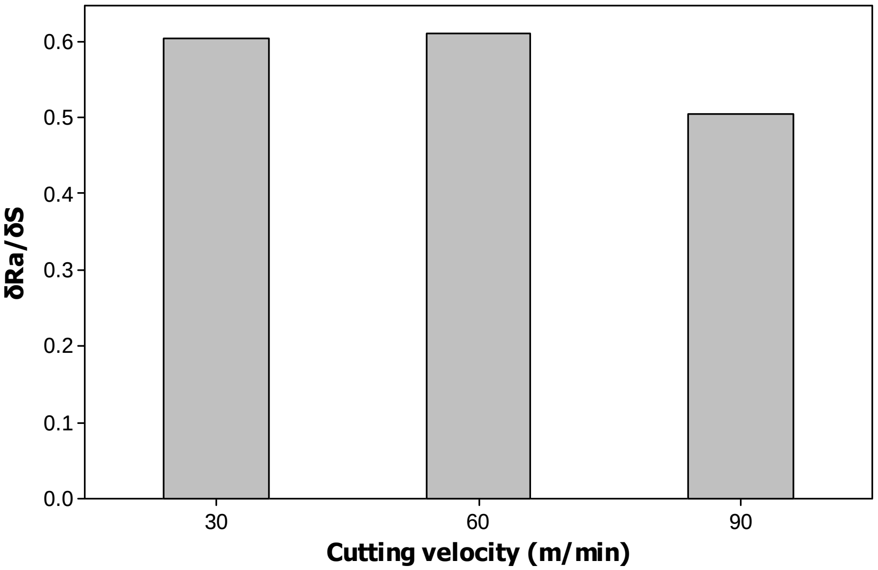

Figure 9. Sensitivity analysis result of wt% of SiC_P

6. Conclusion

The paper examines the influence of depth of cut, the cutting speed and weight percentage of SiC in the metal matrix on surface roughness in plain turning of LM6 Al/SiC metal matrix composites. A functional relationship between the surface roughness and the cutting parameters is established using the principles of Response Surface Methodology. The goodness of fit between the developed model and the experimental results is further evaluated through Analysis of Variance and F-ratio test. In the light of the above analysis, the following conclusions are established:

- The proposed empirical model predicts surface roughness to within 95% confidence level.
- The linear, the quadratic and the interaction terms are all significant for estimation of surface roughness.
- The best surface finish is associated with the lowest level of weight percentage of SiC_P, the lowest level of depth of cut and highest level of the cutting speed.
- The surface roughness is most sensitive to variation in the cutting velocity and the depth of cut.

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