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APPLICATION OF TAGUCHI AND RESPONSE SURFACE METHODOLOGIES FOR METAL REMOVAL RATE AND SURFACE ROUGHNESS IN GRINDING OF DRAC'S

[1]Pai Dayanand , [2]Rao Shrikantha & [3]Shetty Raviraj
[1,3] Department of Aero and Auto Engineering, Manipal Institute of Technology, Manipal University, Manipal. India.
[2] Department of Mechanical Engineering, National Institute of Technology Karnataka, Suratkal, India

ABSTRACT
Efficient grinding of high performance metal matrix composites can be achieved through proper selection of grinding process parameters to maximise metal removal rate and to improve surface integrity. Lowering the grinding costs by using faster metal removal rates is constrained primarily by the surface and sub surface damage which leads to surface quality degradation. Hence this paper deals with study on effect of grinding process parameters on metal removal rate (MRR) and surface roughness on surface grinding of Al6061-SiC composites using Taguchi's design of Experiments. Further by Analysis of Variance, a complete realization of the grinding parameters and their effects were achieved. The variation of metal removal rate and surface roughness with grinding process parameters was mathematically modelled using response surface methodology. Finally the developed model is validated with the set of experiments. It is observed that developed model is in close agreement with the experimental results.

KEYWORDS - Metal Matrix Composites (MMC), Metal Removal Rate (MRR), Surface Roughness, Taguchi's Design of Experiment, ANOVA, Response Surface Methodology (RSM)

1. INTRODUCTION

Discontinuously reinforced aluminium composites(DRACs) is one of the important composites among the metal matrix composites, which have hard SiC particles reinforced in relatively soft aluminium matrix which pose many problems in machining[1]. The DRACs is rapidly replacing conventional materials in various automotive, aerospace and automobile industries. But grinding of DRACs is one of the major problems, which resist its widespread engineering application [2].

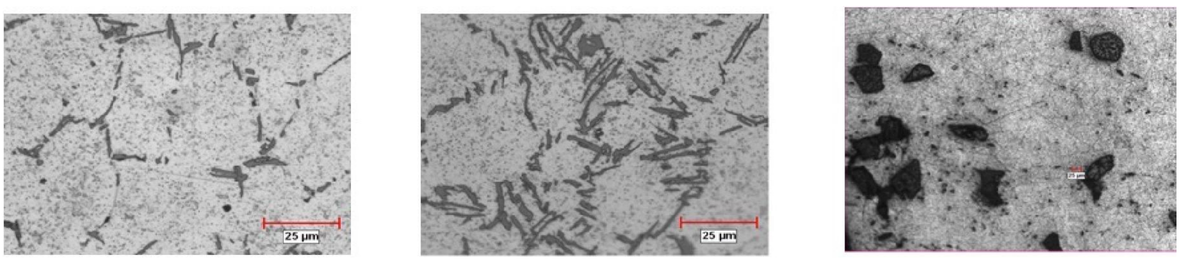
When Al/SiC-MMC specimen slides over a hard cutting tool edge during grinding, due to friction, high temperature and pressure the particles of Al/SiC-MMC adhere to the grinding wheel which affects the surface quality of the specimen [2]. Hence, cost effective grinding with generation of good surface finish on the Al/SiC-MMC specimen during the grinding operation is a challenge to the manufacturing engineers in practice. It is well known, the grinding process does not perform very well for soft materials due to the tendency of the chips to clog the wheel. However, the grinding process plays an important role in secondary machining operations on MMC parts due to the free cutting tendency of these materials [2]. MRR is an important performance parameter in productivity enhancement for grinding process. Very low value of MRR is mainly due to the rubbing and ploughing of the wheel on the workpiece. It is a well-known fact that a high MRR and a very good surface finish can never be achieved simultaneously in a grinding process. This is an age-long problem and continuous efforts are being done by different researchers all over the world to fulfill such an objective. [3].

In view of these above-mentioned grinding problems, the main objective of our work is to study the influence of volume percentage of SiC, feed and depth of cut on MRR and surface finish. Further a mathematical model is developed for MRR and surface roughness based on the experimental data.

A Di Ilio et.al [4] investigated the machining characteristics of Al2009, Al2009-SiC_{15P}, Al2009-SiC_{20P} and Al2009-SiC_{25P}, and concluded that composite shows better surface finish than the pure aluminium. Zhong et.al [5] conducted experiments on grinding of Al2618-Al_2O_3 composites using SiC wheel and diamond wheel and found that SiC wheel is suitable for rough grinding and diamond wheel for finish grinding. Krishnamurthy et.al [6] conducted experiments with powder compacted Al2124-SiC composites. The study revealed that surface finish obtained from Resin bonded wheel is better compared to the electroplated wheel. A Di Ilio et.al [7] in another investigation developed a model of the grinding process based on empirical relations and observed that workpiece surface roughness can be related to the equivalent chip thickness through a power relationship; it shows a decreasing linear trend as the hardness of workpiece material increases. Box and Draper [8] proposed central composite rotatable design for fitting a second order response surface based on the criterion of rotatability. Kwak and Kim [9] developed a second order response surface model for surface roughness and grinding force on grinding of Al/SiC/Mg composites. They observed that the optimum content of SiC and Mg in AC8A aluminium alloy is 30wt% and 9wt% respectively. Kwak [10] presented the application of Taguchi and RSM for the geometric error. A second-order response model for the geometric error was developed and the utilization of the response surface model was evaluated with constraints of the surface roughness and the MRR. Krajnik et.al [11] developed a RSM model for minimisation of surface roughness for centerless grinding of 9SMn28 material. Jones et.al [12] used RSM and Taguchi design to optimise the semiconductor manufacturing process. Zhang et.al [13] conducted a study on solder joint reliability to optimise the fatigue life of the joint.

2. EXPERIMENTAL PROCEDURE

Al6061-SiC specimens containing 8 vol.%,10 vol.% and 12 vol.% of silicon carbide particles of mean diameter 35µm were manufactured at Vikram Sarbhai Space Centre (VSSC) Trivandrum by Stir casting process with pouring temperature 700-710°C, stirring rate 195rpm. The specimen was extruded at 457°C, with extrusion ratio 30:1, and direct extrusion speed 6.1m/min to produce length Ø22mm cylindrical bars. The extruded specimens were solution treated for 2 hours at a temperature of 540^0C in a muffle furnace; Temperatures were accurate to within ±2^0C and quench delays in all cases were within 20s. After solution treatment, the samples were water quenched to room temperature. Further the specimen is machined to 17mm square cross-section. Figure 1 shows the microstructure of Al6061 SiC specimens. The chemical composition of Al 6061 alloy is given in Table 1. Grinding method as machining process was selected



(a) (b) (c)

Figure 1:Microstructure of Al6061-SiC composites with (a) 8 vol% SiC (b) 10 vol% SiC (c) 12 vol% SiC

Table 1: Chemical composition of Al 6061 alloy

Element	**Cu**	**Mg**	**Si**	**Cr**	**Fe**	**Al**
Weight %	0.25	1	0.6	0.25	0.2	Balance

Experiments were performed on 1.5 HP, 2880rpm, conventional surface grinding machine (Bhuraji make) with automatic (hydraulic) table-feed and Norton make diamond grinding wheel ASD76R100B2. The honing stick GN0390220K7V7 is used for dressing the wheel. The experimental setup is shown in Figure 2.

Figure 2: Experimental setup

The experiments were conducted with three levels and three factors. Hence there will be 3^3=27experimental runs with no repetition. Vol % of SiC, table feed and depth of cut are the input factors and metal removal rate and surface roughness are the performance measures. The levels and factors selected for the experimentation are given in Table 2. Selection of factors for optimization was based on preliminary experiments [14] and known instrumental limitations. Metal removal rate is calculated by volume of material loss per unit time during grinding process. The surface roughness of the specimen is measured using Taylor/Hobson surtronoic 3^+ surface roughness measuring instrument.

Table 2: Levels of independent Factors

Factors	**Levels**		
	Low(1)	**Medium(2)**	**High(3)**
Percentage SiC (X_1)	8	10	12
Feed (mm/s) (X_2)	60	70	80
Depth of Cut (µm) (X_3)	8	12	16

3. DESIGN OF EXPERIMENTS

In an experiment, deliberate changes to one or more process variables (or factors) are made in order to observe the effect that those changes have on one or more response variables. Design of experiments (DOE) is an efficient procedure for planning experiments so that the data obtained can be analyzed to yield valid and objective conclusions. Before any attempt is made to use this simple model as a predictor for the measures of performance, the possible interactions between the control factors must be considered. In order to understand a concrete visualization of the impact of various factors and their interactions, it is desirable to develop analysis of variance (ANOVA) to find out the order of significant factors as well as their interactions.

a. Taguchi's Method

Taguchi techniques have been used widely in engineering design. This method is useful for studying the interactions between the parameters, and also it is a powerful design of experiments tool, which provides a simple, efficient and systematic approach to determine optimal process parameters. Compared to the conventional approach of experimentation, this method reduces drastically the number of experiments that are required to model the response functions. Taguchi has used Signal–Noise (S/N) ratio as the quality characteristic of choice. The S/N ratio characteristics can be divided into three categories given by Eqs. (1) – (3), when the characteristic is continuous.

Nominal is the best characteristic

$$\frac{S}{N} = 10 \log \frac{\bar{y}}{s_y^2} \tag{1}$$

Smaller is the best characteristic

$$\frac{S}{N} = -10 \log \frac{1}{n}\left(\sum y^2\right) \tag{2}$$

and larger the better characteristic

$$\frac{S}{N} = -\log \frac{1}{n}\left(\sum \frac{1}{y^2}\right) \tag{3}$$

Where $\bar{y}$ the average of observed data, s_y^2 is the variation of y, n is the number of observations, and y is the observed data. For each type of the characteristics, with the above S/N ratio transformation, the smaller the S/N ratio the better is the result when we consider tool wear, surface roughness, cutting force, cutting temperature and stress.For the elaboration of experiment plan, we used the method of Taguchi for three factors at three levels. The array chosen was the L27 (3^{13}) which have 27 rows corresponding to the number of tests (26 degree of freedom) with 13 columns at three levels.

The plan of experiments is made of 27 tests in which first column was assigned to the first input parameter and the second column to be second input parameter and the fifth column to be the third input parameter and the remaining were assigned to the interaction.

b. Response surface methodology

In order to investigate the influence of various factors on the MRR and surface roughness (SR), three principal factors such as the volume percentage of SiC (X_1), feed (X_2) and depth of cut (X_3) were taken. In this study, these factors were chosen as the independent input variables. The desired responses were the MRR and surface roughness (SR) which are assumed to be affected by the above three principal factors. The response surface methodology (RSM) was employed for modeling and analyzing the machining parameters in the grinding process so as to obtain the machinability performances of responses. RSM is a collection of statistical techniques that are useful for the modeling and analysis of problems in which one or more responses of interest are influenced by several variables and the objective is to find the relationship between the responses and several variables and optimise the responses. [15].

In many engineering fields, there is a relationship between an output variable of interest 'y' and a set of controllable variables {x_1, x_2 . . . .x_n}. In some systems, the nature of the relationship between y and x values might be known. Then, a model can be written in the form [16]

$$y = f(x_1, x_{2,} .... x_n) + \varepsilon \tag{4}$$

where ε represents noise or error observed in the response y. If we denote the expected response be

$$E(y) = (x_1, x_2, ... x_n) = y$$

then the surface represented by

$$\hat{y} = f(x_1, x_2, ... x_n) \tag{5}$$

is called response surface. The first step in RSM is to find a suitable approximation for the true functional relationship between response y and set of independent variables employed. Usually a second order model is utilized in response surface methodology [17]

$$\hat{y} = \beta_0 + \sum_{i=0}^{k} \beta_i x_i + \sum_{i=0}^{k} \beta_i x_i^{\,2} + \sum_{i<j}\sum \beta_{ij} x_{ij} + \varepsilon \tag{6}$$

4. RESULTS AND DISCUSSION

a. Effect of Grinding Parameters on Metal Removal Rate and Surface Roughness

Experiments are conducted with three factors at three levels L27 orthogonal array. Table 3 shows the experimental results for MRR and Surface Roughness.

b. Analysis of Variance (ANOVA)

On the examination of the percentage contribution (P%) of the different factors for MRR, (Table 4), it can be seen that feed X_2 (P=46.82%) and depth of cut X_3 (P=44.73%) has the highest contribution. Thus feed and depth of cut are the important factor to be taken into consideration while grinding DRACs. It can be seen that SiC vol %, X_1 (P=5.53%) and interactions X_1* X_2 (P=1.8%) and X_2* X_3 (P=1.11%) have statistical and physical significance on MRR. The interaction (X_1* X_3) neither present a statistical significance, nor a percentage of physical significance of contribution to the MRR

The percentage contribution for surface roughness is given in Table 5. It can be seen from the table that, other than interaction (X_2*X_3) all the factors have statistical and physical significance on surface roughness.

Table 3: Experimental results for MRR and surface roughness

Trial No	Levels of Factor			Response	
	Vol. % SiC (X_1)	Feed (X_2, mm/s)	DOC (X_3, µm)	MRR (mm^3/s)	surface roughness (microns)
1	8	60	8	7.324	1.05
2	8	60	12	9.959	1.07
3	8	60	16	11.915	1.13
4	8	70	8	6.381	1.10
5	8	70	12	7.894	1.14
6	8	70	16	9.602	1.19
7	8	80	8	6.054	1.15
8	8	80	12	7.601	1.24
9	8	80	16	8.962	1.29
10	10	60	8	9.857	0.81
11	10	60	12	12.310	0.85
12	10	60	16	14.654	0.89
13	10	70	8	6.799	0.86
14	10	70	12	8.379	0.91
15	10	70	16	9.877	0.95
16	10	80	8	6.553	0.92
17	10	80	12	7.927	0.97
18	10	80	16	9.505	1.04
19	12	60	8	9.293	0.62
20	12	60	12	12.002	0.73
21	12	60	16	14.102	0.80
22	12	70	8	6.849	0.65
23	12	70	12	8.557	0.75
24	12	70	16	10.123	0.82
25	12	80	8	6.644	0.69
26	12	80	12	8.201	0.76
27	12	80	16	9.553	0.85

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Table 4: Analysis of variance for means of MRR

Source	Degrees of Freedom	sum of square	Mean square	F-ratio	P-value	P%
X_1	2	7.279	3.6394	550.29	0.000	5.53
X_2	2	61.619	30.8093	4658.49	0.000	46.82
X_3	2	58.873	29.4367	4450.94	0.000	44.73
X_1* X_2	4	4.737	1.1842	179.05	0.000	1.80
X_1* X_3	4	0.034	0.0085	1.28	0.352	0.013
X_2* X_3	4	2.923	0.7306	110.48	0.000	1.110
Residual Error	8	0.053	0.0066			

Total	26	135.517

Table 5: Analysis of variance for means of surface roughness

Source	Degrees of Freedom	sum of squares	Mean square	F-ratio	P-value	P%
X_1	2	0.764	0.3821	1671.1	0.000	85.78
X_2	2	0.051	0.0257	112.3	0.000	5.76
X_3	2	0.069	0.0343	149.99	0.000	7.70
$X_1 * X_2$	4	0.008	0.0019	8.3	0.006	0.43
$X_1 * X_3$	4	0.005	0.0013	5.6	0.019	0.29
$X_2 * X_3$	4	0.001	0.0002	0.75	0.587	0.04
Residual Error	8	0.002	0.0002			
Total	26	0.899				

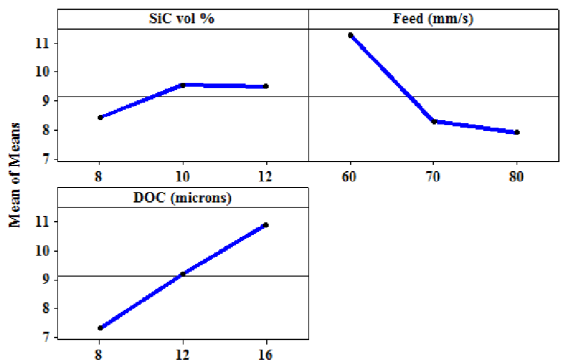


Figure 3: Main effect plot for MRR

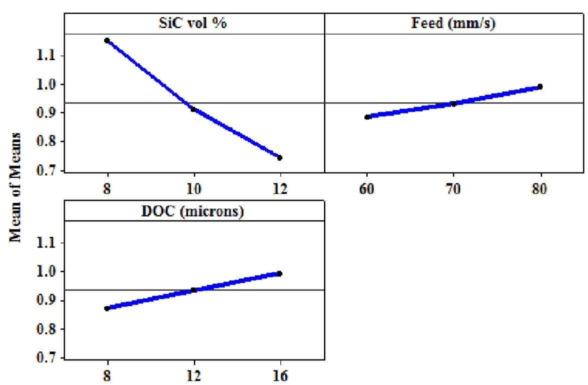


Figure 4: Main effect plot for surface roughness

From the observed data for MRR and surface roughness (SR), the response function has been determined in uncoded units as

$$MRR=42.4576+4.0029X_1-1.8034X_2+1.7716X_3-0.1221X_1^2+0.014X_2^2-0.0235X_3^2-0.0186X_1X_2+0.0034X_1X_3-0.0112X_2X_3 \quad ---(7)$$

and

$$Ra=2.1305-0.2204\,X_1+0.00576\,X_2-0.0147\,X_3+0.00874\,X_1^2+6.61E\text{-}05\,X_2^2-1.08E\text{-}04\,X_3^2-0.00117\,X_1X_2+0.002093\,X_1X_3+0.000168\,X_2X_3 \quad \text{--------}\ (8)$$

Figure 3 shows the main effect plot for MRR. It is observed for the figure that, MRR increases with increase in SiC volume percentage, decrease in feed and increase in depth of cut. Hence it is economical to ground the Al-SiC specimen having 12 vol% of SiC with low feed and high depth of cut.

Figure 4 is the main effect plot for surface roughness. It can be concluded for the figure that surface roughness decrease with increase in SiC vol%, decrease in feed and decrease in depth of cut. Response Surface Analysis for MRR and Surface Roughness

The result of ANOVA for the response function MRR and surface roughness are presented in Table 6 and 7. This analysis is carried out for a level of significance of 5%. The standard percentage point of F distribution for $F_{0.05,3,17}$ is 3.20. Since tabulated F-values are greater than the standard F-value, both the models are adequate at 5% significance limit [18].

From equation (7) surface and contour plot for MRR at different feed and depth of cut are plotted (Figure 5(a) and (b)). These response contours and surface plot can help in the prediction of the MRR at any zone of the experimental domain. It is clear from these plots that the MRR increases with the increase in depth of cut and decrease in feed

Table 6. Analysis of Variance for MRR

Source	DOF	Seq. Sum of Square	Adj. Mean Square	F-Value	P-Value
Regression	9	131.85	14.65	68.08	0.000
Linear	3	115.37	38.457	178.71	0.000
Square	3	12.392	4.1308	19.2	0.000
Interaction	3	4.088	1.3627	6.33	0.004
Residual error	17	3.658	0.2152		
Total	26	135.51			

Table 7. Analysis of Variance for surface roughness

Source	DOF	Seq. Sum of Square	Adj. Mean Square	F-Value	P-Value
Regression	9	0.89413	0.09934	356.81	0.000
Linear	3	0.8761	0.0.292	1048.85	0.000
Square	3	0.00763	0.0.002	9.14	0.001

Interaction	3	0.0104	0.00346	12.45	0.000	Total	26	0.89887
Residual errror	17	0.00473	0.00027					

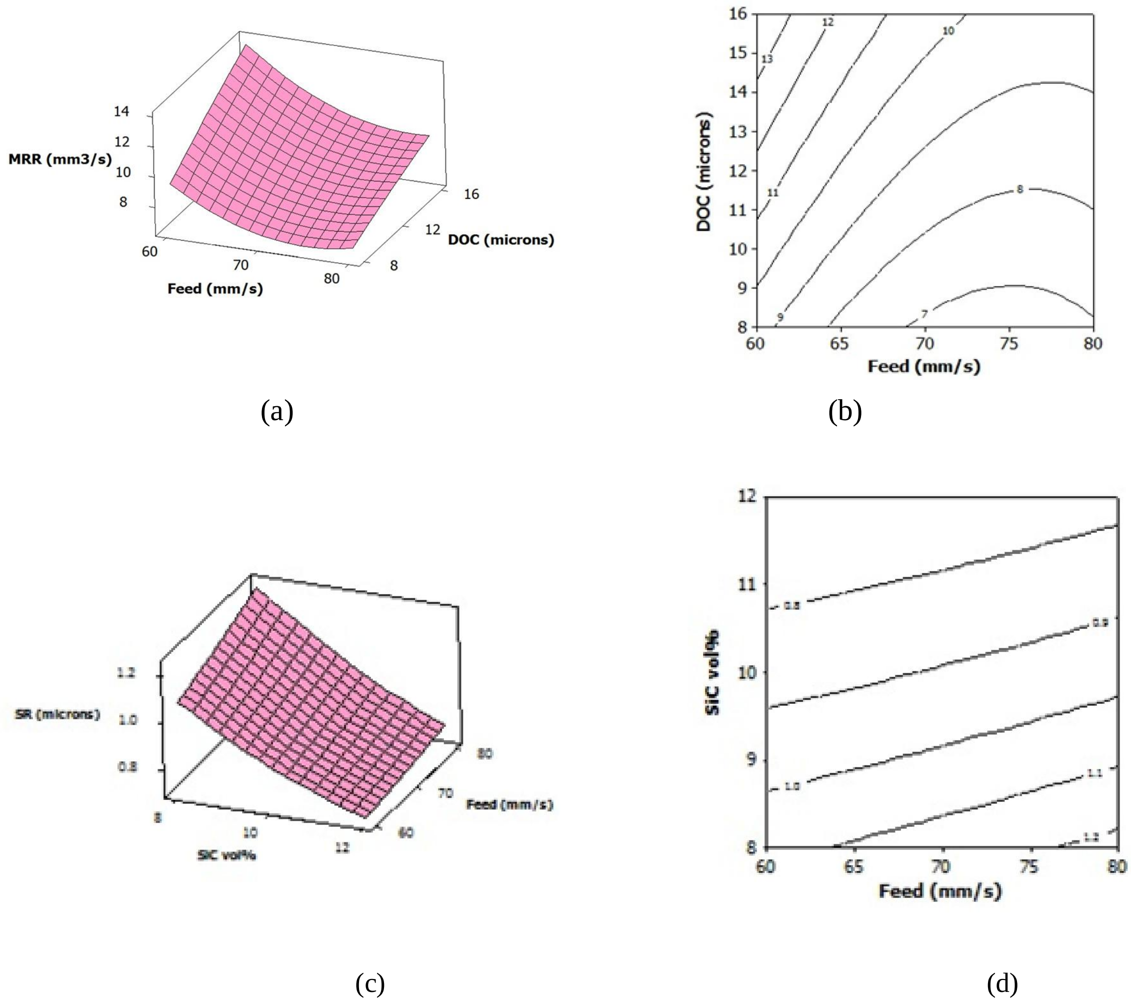
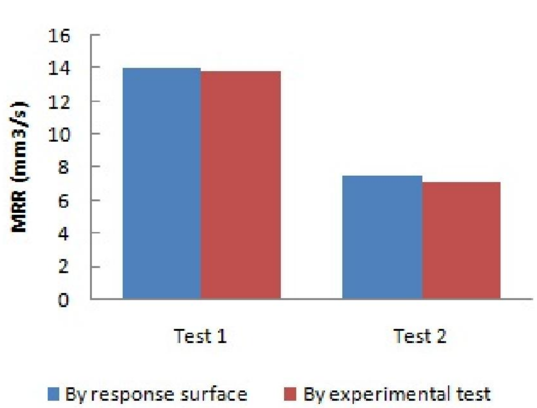


Figure 5: (a) Surface plot for MRR (b) Contour plot for MRR (c) Surface plot for surface roughness (d) Contour plot for surface roughness

From equation (8) surface and contour plot for surface roughness at different depth of cut and SiC vol% are plotted (Figure 5(c) and (d)). It is observed from the plots that surface roughness will improve with decrease in depth of cut and increase in SiC vol%.



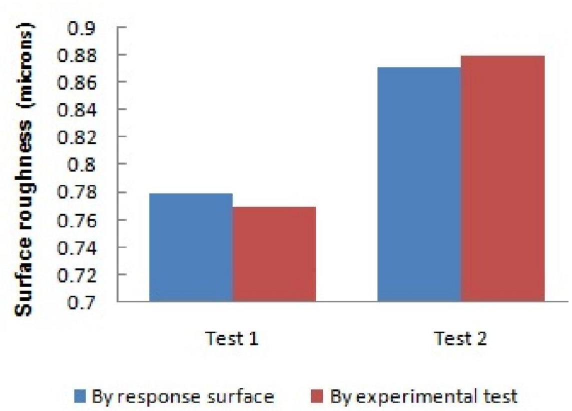


Figure 6: (a) Confirmation test for MRR. (b) Confirmation test for surface roughness.

5. CONFIRMATION EXPERIMENTS

In confirmation of the second-order response surface model (Eq. 7 & Eq. 8), verification tests were conducted. One test was performed for the test conditions given in trial number 21 of Table 3 (Test 1), and another at the selected condition (Tests 2) that was not carried out in Table 3. In test 2, Al-6061-10%vol SiC (factor A), feed 70mm/s (factor B), and depth of cut 10µm (factor C), were used. Figure 6 (a) and (b) shows the test results. It can be observed from the figure that the results obtained from the developed models and the experimental results are in close agreement with each other.

6. CONCLUSION

In this study, the Taguchi's method and Response surface methodology was applied for analyzing MRR and surface roughness in the surface grinding of DRACs. Based on experimental work, following conclusions were drawn.

- Increase in volume percentage of SiC will improve the surface roughness due to the reason that, increase in percentage of SiC will increase the hardness of the specimen, which results in decrease ploughing of the wheel during grinding. It is also observed that MRR will increase with increase in depth of cut.
- ANOVA is used to study the effect of different factors on MRR and surface roughness. It is observed that MRR is predominantly affected by feed followed by depth of cut and volume percentage of SiC. Whereas surface roughness is more dependent on volume percentage of SiC, followed by depth of cut and feed.
- Response surface methodology is used to develop a second order equation for surface roughness and MRR in terms of the process variables. It is observed that fitted value is very close to the experimental value. (adj-$R^2 \sim 0.97$)
- Confirmation tests were performed to validate the second order response surface model for MRR and surface roughness. The predicted test results are in conformance to the experimental test results.

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