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Experimental Analysis on Surface Roughness in Turning Hybrid Metal Matrix (6061Al+SiC+Gr) Composites

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Owing to the distinguished properties Metal Matrix Graphite Hybrid Composites (Al/SiC-MMC-Gr) are used in various applications. This paper deals with the utility of Taguchi and response surface methodologies for the prediction of surface roughness in tuning of these materials with PCD tool. The cutting parameters effect on surface quality is analyzed and an empirical model with respect to turning parameters is established using response surface method. The most important parameter that influences the turning Al/SiC-MMC-Gr is feed. The measured and predicted results are approximately equal, which proves that, model is to be used for predicting surface finish in turning of these composites. Validation experiments have been used to confirm the predicted results.

Keywords: hybrid metal matrix composites, Taguchi method, turning, response surface method (RSM), surface roughness, PCD tool.

1. Introduction

Owing to their distinguished properties, Metal Matrix Graphite Hybrid Composites (Al/SiC-MMC-Gr) have an extensive utilization in many applications. The distinguished properties required for aerospace and automobile are unattainable in lightweight monolithic titanium, Magnesium and Aluminum alloys [1]. Particle reinforced MMCs amidst other metal matrix composite materials have found an extensive utilization owing to their distinguished properties such as high mechanical properties and better wear resistance. Amidst the available commercial compositions, matrix silicon carbide reinforced aluminum is the commonest [2].

The advantages of Metal Matrix Composites (MMCs) have been appreciated for many years. The soft matrix like aluminium and the reinforcement like ceramic materials control the properties of these composites. The most prominent form of MMCs is aluminum embedded with hard ceramic particles. Long fiber MMCs have got an ample scrutiny owing to economic and improved properties compared with monolithic alloys [3-5]. These economic composites yield stiffness, fatigue resistance and higher strength with nominal density. The machining process is made easy by the addition of lubricating materials like graphite or mica.

Many researchers have reported about the manufacturing and machining method for MMCs. The cutting speed influence on chip designing, cutting tool designing and surface of the turned surface have been investigated by Yusuf Ozcatalbas [6]. The tool wear in the machining of these materials has been investigated by Ciltci et al. [7]. Karthikeyan and Palanikumar [8] have investigated the parameter impact on surface finish. Both have the opinion that, the feed rate is the effective parameter in machining metal matrix composites. Manna and Bhattacharya [9] have investigated the influential parameters and have indicated that machined surface quality is one of the crucial factors that influence the uses of the composites. Surface finish is an important design feature for the manufacturability of materials subject to fatigue loads. Besides, tolerances in process planning, have a critical constraints in selecting the cutting parameters [10]. Using diamond coated tools, Davim has investigated about the machinability of MMC composites and reported that diamond tools perform better [11].

Rajmohan and others [12] have made surface integrity study in machined hybrid MMCs reinforced with SiC and Mica. The results have shown that the raising of spindle speed decreases the surface roughness, whereas, it rises with an increase in the feed. Taskesen and Kutukde [13] have performed the experimental study on B_4C reinforced metal matrix composites. They have declared that, the roughness is minimized with the escalation of B_4C content for carbi de drills. Joardar et al. [14] have evaluated the variables effect on cutting force in machining of MMCs. They have applied response surface method for optimizing the cutting parameters. Lately, Rajmohan et al. [15] have applied grey-fuzzy algorithm to optimize cutting parameters for drilling A1356 SiC-mica. Rajmohan et al [16] have used Taguchi technique with grey relational analysis. The result indicates that drill type and feed rate play an important role in deciding performance. Composite materials in which two or more high performance reinforcements are combined and they are called hybrid Composite. Tool wear at all cutting condition is reduced by the incorporation of graphite in aluminum silicon carbide metal matrix composite [17]. In this research work, graphite has been added to the composite for reducing the amount of PCD tool wear and it improves the surface roughness.

Surface finish is one of the required properties to decide the manufacturability of composite products. For getting the functionality of a part, the desired surface quality is of great importance. Minimization of surface roughness in manufactured composite part is a serious task and it is important to have prediction models to achieve the better results. Response Surface Method (RSM) is an important method applied in the prediction of responses. As an illustration, Palanikumar [18] has examined the usage of RSM and Taguchi method for making surface roughness model. Many researchers have employed this technique successfully.

This paper evaluates the machining parameters effect for minimum rough surface in turning of Al /SiC MMC-Gr hybrid materials by Poly-Crystalline Diamond (PCD) tool. For conducting and analyzing the experiments, Taguchi's method with response surface methodology (RSM) is employed. The effectiveness is checked by using coefficient of correlation.

2. Methods and materials

In the design of experiments, Taguchi method is one of the significant methods to combat results, which is influenced by number of variables. Conventional experimental design procedures are too difficult, if more variables are considered. To conduct the experiment, a careful planning of design is required. Taguchi's design makes use of specially arranged orthogonal arrays [19,20]. This design scheme has less number of experiments, when it is compared to the other experimental method. In Taguchi's method, for analyzing the parameters, Signal-to-noise ratio is used.

Response Surface Method (RSM) consists of statistics and mathematics. This method relates the "response variable y" and the "input variables such as x_1, x_2,... $x_{k''}$. Box and Wilson in the early 1950s have introduced this method [21]. In various situations, many researchers have used this technique with considerable success [24, 25]. This method is used for the prediction and also for the analysis of the parameters. A6061 A1+SiC+ Grphite composites are made in the laboratory by using the suitable setup. The set up includes a crucible furnace made of graphite, a stirrer motor arrangement, an argon tank and a control unit. At first, the A6061 aluminium is melted in the crucible by suitable temperature. The reinforcement particles such as silicon carbide and graphite in the powder form are preheated by using a suitable furnace for about 3 hours. The preheated reinforcements are then added to the molten aluminium. The stirrer motor is used to mix the combination thoroughly. The Argon gas chamber pressure of 2 bar is used to cool the hybrid MMC. The fabricated metal matrix composite is presented in Fig. 1.

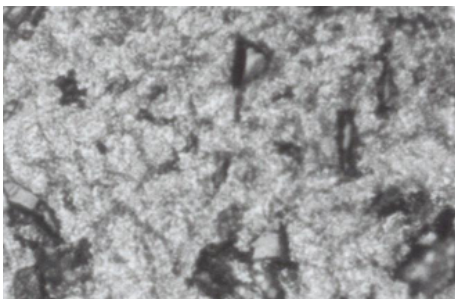

Figure 1 Microstructure of the composite fabricated (A6061- 90%; SiC-5%; Graphite - 5%)

For experiments, Taguchi method having L_{27} orthogonal array is used with three levels of factors. The variables considered are: cutting speed (V), feed (f), and depth of cut (d). The parameters affect the process and the levels (Table 1) have been arrived from previous experience of authors and the related sources available.

Table 1 Process parameters and their levels

S. No	Parameter	Notation	Unit	Levels		
				1	2	3
1.	Cutting speed	V	m/min	75	125	175
2.	Feed	f	mm/rev	0.1	0.2	0.3
3.	Depth of cut	d	mm	0.5	1	1.5

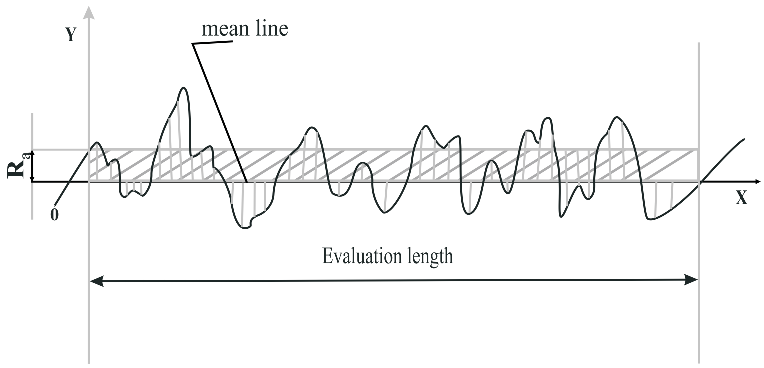

Figure 2 Definition of the arithmetic average height (R_a)

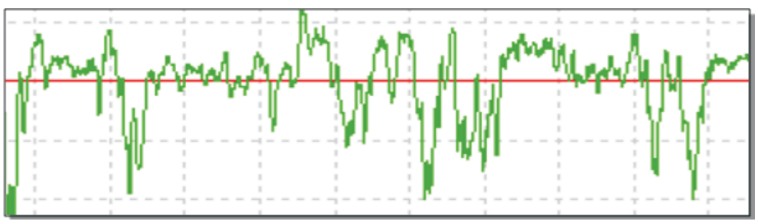

Figure 3 Typical surface profile observed in machining of Hybrid-MMC composites

The work piece A 6061-90%, SiC-5%, Graphite-5% has the diameter 50mm and length 175 mm and the cutting operation is performed by using Polycrystalline diamond (PCD) tools. The PCD tools used here have an excellent performance than the carbide and other tools. The cutting tool designation used is CNMG 120408 and the tool holder considered is PCLNR 2525 M 12. The cutting experiments are performed by using HMT make Computer numeric controlled Lathe. The response considered is surface roughness with a view to analyze the surface finish quality. The following mathematical relationship expresses the arithmetic average of the surface roughness (R_a) as:

$$R_a = \frac{1}{L}\int_0^L [Y\,(x)]\,dx \tag{1}$$

where R_a is an arithmetic average deviation from the mean line and Y is ordinate of the profile curve and L is the sampling length. The definition and the typical profile perceived in turning are exhibited in Figs. 2 and 3. Surface roughness is measured by using Taylor Hobson tester, UK. The observed values are presented in the Table 2.

3. Results and discussions

3.1. *Analysis of S/N ratio*

In Taguchi's method, the product performances and quality are improved by using a loss function, which is perceived from the statistical analysis and engineering as expressed by:

$$L(y) = \frac{L"(m)(y-m)^2}{2!} = k(y-m)^2 = k(MSD) \tag{2}$$

where *L(y)* is the loss function, y is the value of the quality characteristic, and m is the targeted value of y. k, the proportionality constant, is dependable on financial criticality of y and *MSD* is the mean square deviation. In Taguchi's analysis, signal-to-noise ratio (μ) is used; the Equation (3) is expressed as:

$$\eta = -10\log_{10}(MSD) \tag{3}$$

Smaller values are at all times preferred in the event of surface roughness, the S/ N ratio for "smaller – the – better" is calculated as:

$$\eta = -10\log_{10}\left(\frac{1}{r}\sum_{i=1}^{r} R_i^2\right) i = 1,\, 2, \ldots,\, r \tag{4}$$

where R_i indicates the response for the ith test, "r" is the required no. of experiments. The computed S/N based on the roughness is presented in Table 2. The effect of parameters from lower level to higher level is analyzed by means of using effect graphs. The effect graph plotted based on the Analysis of Means (ANOM) is presented in Fig. 4, which shows, how the mean for each level of a factor compares to the overall mean (also called the grand mean). Table 3 illustrates the response table, which indicates the changes in the roughness at different levels.

Table 2 Experimental data and their *S/N* ratio (dB)

Expt. No.	Cutting speed, m/min.	Feed, mm/rev.	Depth of cut, mm	Surface roughness, Ra, m*			S/N ratio, dB
				1	2	3	
1.	75	0.1	0.5	2.54	2.52	2.50	-8.02819
2.	75	0.1	1.0	1.84	2.25	2.36	-6.69556
3.	75	0.1	1.5	2.12	2.32	1.92	-6.55241
4.	75	0.2	0.5	3.26	3.18	3.05	-10.0061
5.	75	0.2	1.0	2.45	2.64	2.56	-8.13485
6.	75	0.2	1.5	2.54	2.48	2.39	-7.85664
7.	75	0.3	0.5	3.42	3.77	3.28	-10.8716
8.	75	0.3	1.0	2.84	3.05	2.78	-9.22492
9.	75	0.3	1.5	2.48	2.72	2.67	-8.38381
10.	125	0.1	0.5	2.32	2.18	2.28	-7.08512
11.	125	0.1	1.0	1.84	1.72	1.66	-4.81901
12.	125	0.1	1.5	2.03	2.19	1.75	-6.01317
13.	125	0.2	0.5	2.95	2.56	2.76	-8.82215
14.	125	0.2	1.0	1.96	2.28	2.48	-7.04448
15.	125	0.2	1.5	2.52	2.21	2.38	-7.50737
16.	125	0.3	0.5	3.28	3.14	3.15	-10.0775
17.	125	0.3	1.0	2.68	2.75	2.51	-8.46028
18.	125	0.3	1.5	2.73	2.78	2.95	-9.00982
19.	175	0.1	0.5	1.84	1.62	1.73	-4.77261
20.	175	0.1	1.0	1.64	1.59	1.63	-4.19107
21.	175	0.1	1.5	1.52	1.73	1.88	-4.69218
22.	175	0.2	0.5	2.08	2.34	2.15	-6.8198
23.	175	0.2	1.0	2.17	1.84	1.71	-5.65005
24.	175	0.2	1.5	1.75	2.25	2.12	-6.23917
25.	175	0.3	0.5	2.38	2.56	2.83	-8.28808
26.	175	0.3	1.0	2.34	2.33	2.06	-7.03237
27.	175	0.3	1.5	2.42	2.74	2.37	-8.01196

*Average of 3 results

Table 3 Response Table for signal to noise ratio

Level	Cutting speed, m/min.	Feed, mm/rev.	Depth of cut, mm
1	-8.417	-5.872	-8.308
2	-7.649	-7.565	-6.806
3	-6.189	-8.818	-7.141
Delta	2.229	2.946	1.502
Rank	2	1	3

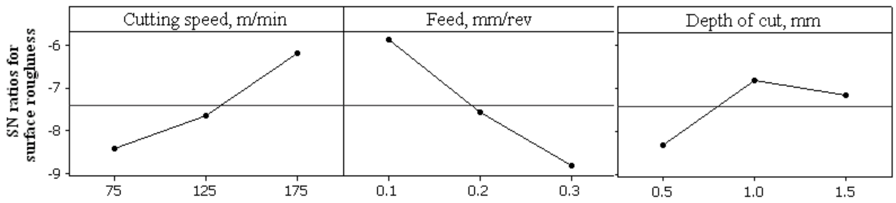

Figure 4 ANOM graph for S/N ratio

From Table 3 and Fig. 4, it has been found that, feed is the parameter that has influence the surface finish, which is followed by cutting speed. The cutting depth has comparatively lower effect. Based on the analysis, it is noticed that, the value of roughness on the surface reduce themselves due to the increase of cutting speed. Also, the chip fracture occurs at low cutting speeds and it produces imperfection on the work piece, which leads to an increase in the roughness and it has been reduced at high speed because of the thermal softening of tool. This result shows that, the surface roughness becomes minimum at the reduced feed. The surface variation observed in hybrid composites is low at low feed while analyzing with high speed, less surface roughness is guided by very small fraction in surface. Linearly, the increase in feed increases the roughness, which is rational to the increased chatter, incomplete machining and increased forces.

The surface roughness reduces up to 1.0 mm cutting depth, and then it raises the surface to some extent. At small cutting depth, the maximum surface roughness is noticed. It is concluded that, the roughness is to a great extent exerted influence by the feed. From the discussion based on the results and evidence from Fig. 4, the optimal solution obtained is:

1. Cutting speed (V) $\approx$ 175 m/min.
2. Feed (f) $\approx$ 0.1 mm/rev.
3. Depth of cut (d) $\approx$ 1.0 mm.

It is brought into prominence that, the above conditions give only a best solution among the tested conditions. For the real optimum solution, further research is required.

3.2. *Response surface analysis*

Generally, in engineering fields, there is a connection between the input variables $\{x_1, x_2, \ldots x_n\}$ and output variable of interest. If the relation is established for some other systems, then, a model is given by:

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

Here, ε represents the error. In other words response be:

$$E(y) = f(x_1, x_2, ...x_n) = \eta \tag{6}$$

Then, the surface is represented by:

$$\eta = f(x_1, x_2, ...x_n) \tag{7}$$

The form of linkage between the variables considered and the response is unknown and it is approximated with the variables and output 'y' is established. Generally, a second order model is used as [18]:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i} \rangle \sum_{j} \beta_{ij} x_i x_j + \varepsilon \tag{8}$$

In second order model, the β coefficients are to be calculated. The model summary statistics for such kind of models is presented in Table 4.

Table 4 Model summary statistics

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS
Linear	0.228796	0.790667	0.782511	0.768322	4.461011
2FI	0.207961	0.833794	0.820318	0.804655	3.761409
Quadratic	0.163491	0.901441	0.888948	0.870715	2.489417

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The measures correlation co-efficient (*R-Sq*) and adjusted *R-Sq* are used to find out whether, the model fits the data well or not. To choose the model with the suitable and best fit, these values mostly help. *R-Sq* is adjusted slightly and so this has changed. *R-Sq* is used to predict the response so as to get cross-validation. Also, the ability of prediction is assessed by the prediction sum of squares (PRESS). Generally, a smaller value of PRESS is preferred. It is asserted from the model summary Table 4 that, no other model considered gives results as good as the quadratic polynomial model. The ANOVA table for Quadratic model has been hypothesized in getting the results. Equation 9 gives the model developed:

$$\begin{aligned} \text{SurfaceRoughness} &= +3.52134 - 3.58519E - 003V + 6.05602f \\ &\quad -2.89435d - 3.35556E - 005V^2 - 2.94444f^2 \\ &\quad +1.01556d^2 + 1.16667E - 03Vf + 5.70000E - 003Vd \\ &\quad -1.04444fd \end{aligned} \tag{9}$$

In order to analyze the effect of factors, the analysis of variance (ANOVA) is applied and the ANOVA result is presented in Table 5.

In ANOVA, "F-ratio" is used for checking the adequacy of the parameters considered in which the "F-table" value is not as great as calculated value of F. The Model F-value of 72.15 suggests from the table (Table 5) that the model is meaningful with significance.

Residual analysis is carried out, which indicates the difference between deserved values and fitted values [22] of the response surface model. The plots in machining hybrid metal matrix composites are exhibited in Figs. 5.

Table 5 Analysis of variance for the response surface model

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	17.35743	9	1.928603	72.15345	< 0.0001	signific.
V	4.926224	1	4.926224	184.3013	< 0.0001	
f	8.552224	1	8.552224	319.9583	< 0.0001	
d	1.746002	1	1.746002	65.32192	< 0.0001	
V^2	0.126672	1	0.126672	4.739098	0.0328	
f^2	0.015606	1	0.015606	0.58384	0.4473	
d^2	1.160272	1	1.160272	43.40844	< 0.0001	
Vf	0.001225	1	0.001225	0.04583	0.8311	
Vd	0.731025	1	0.731025	27.34932	< 0.0001	
fd	0.098178	1	0.098178	3.673055	0.0593	
Residual	1.897772	71	0.026729			
Lack of Fit	0.349572	17	0.020563	0.717224	0.7718	not signific.
Pure Error	1.5482	54	0.02867			
Cor Total	19.2552	80				

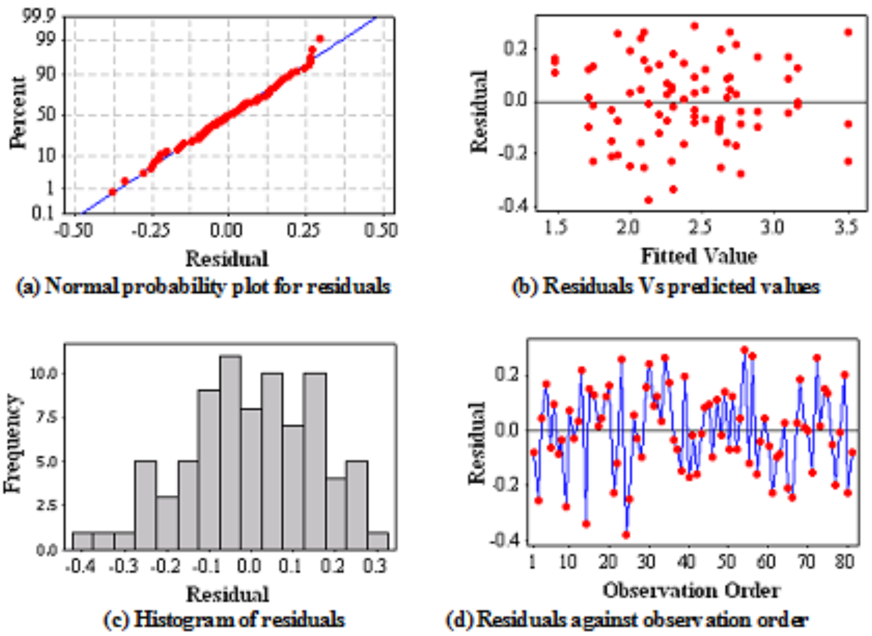


Figure 5 Residuals graph

This provides the additional details of the model. 'Normal probability' for residuals is presented in Fig. 5(a), which is in the form of graph structured on the basis of "Central limit theorem" [23]. The effects of residuals have "real" or "chance", which are examined using usual probability plot. In Figure 5(a), there are data spreading almost in a straight line. They show the good connection existing between experimental results and model. The residual versus predicted value is shown in Figure 5(b), the results show only small difference between the observed and fitted values, which indicate the high correlation. The residual histogram shows the statistics about the residuals, which is indicated by Figure 5(c). Figure 5(d) indicates the residuals, which are calculated against experimentation order. It is declared firmly from figure that, the existence of a main correlation is indicated by having the runs of positive and negative residuals. Wholly with reference to the residual analysis, the plots 5(a)(d) do not have any inadequacy [24], besides, all the residuals are within the limit.

3.3. *Analysis of experimental results*

Studies based on the AI/SiC-Gr hybrid composites are important because, these composites find many applications day-by-day. The properties are increased by the presence of SiC in the metal matrix [5]. The machinability of the aluminum alloy is comparatively easier, when it is compared to the conventional materials by which, continuous chips are produced with good surface finish. The addition of SiC completely changes the chip formation mechanism and related finish [23]. The addition of graphite in Al/ SiC improves the lubrication, which leads to good machinability. The result has indicated that the addition of graphite improves the surface finish by comparing it to the previous study. Figure 6 shows the images of PCD tool, which is observed for the turning of Al /SiC-Gr composites.

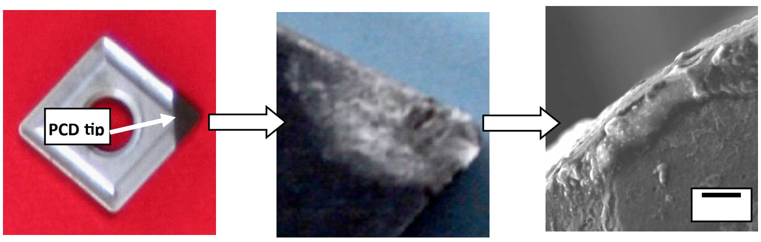


Figure 6 PCD tool used and its close-up view and SEM image

The figure shows the tool, which is used with close-up view after the machining operation and the SEM micrograph is observed after the machining operation. There is a great difference between PCD tool wear observed, when it is compared to the conventional materials. The wear is usually owing to the abrasive action of silicon carbide particles embedded in the composites. The sediments of the molten aluminum matrix are formed on the tool, which is depicted in the figure. The response surface equation is developed for analyzing parameters on machining. Eqn. (9) is used to plot as contours at various depths of cuts, which are presented in Fig. 7. It is understood that, these contours are able to predict the response at any region in which, the experiments are conducted [24]. These figures state that, in the event of increasing of cutting speed roughness of surface falls. It is clear that it increases with the event of the increasing feed. However the results have indicated that the medium depth of cut is preferable in connection with machining of hybrid composites.

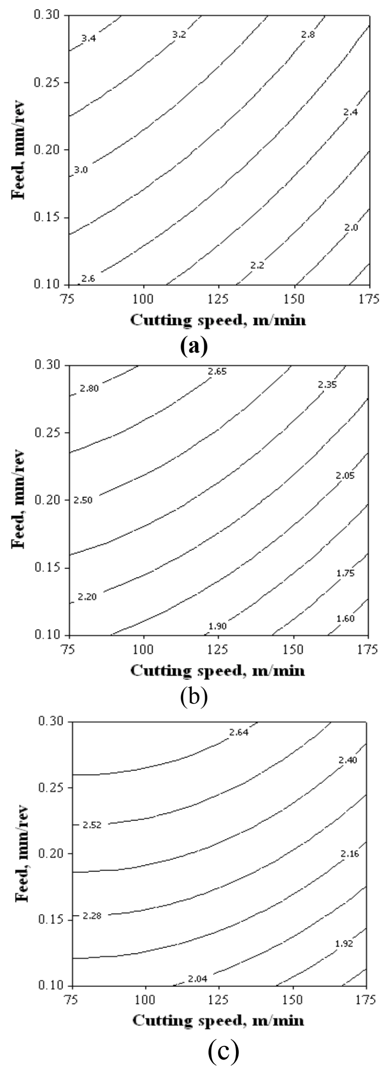
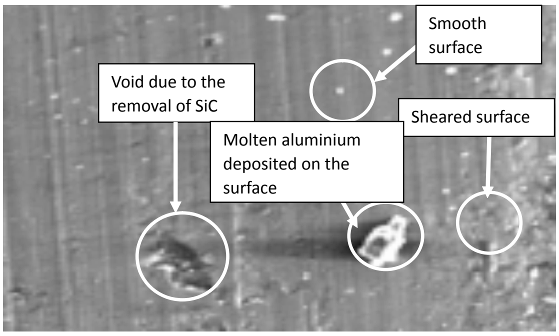
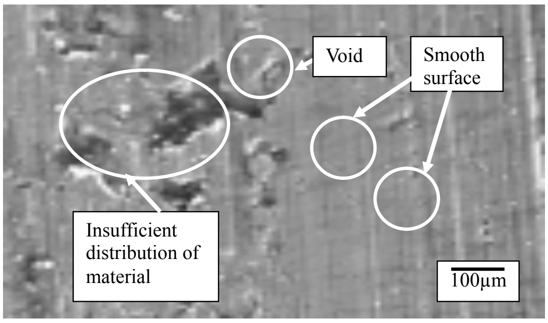


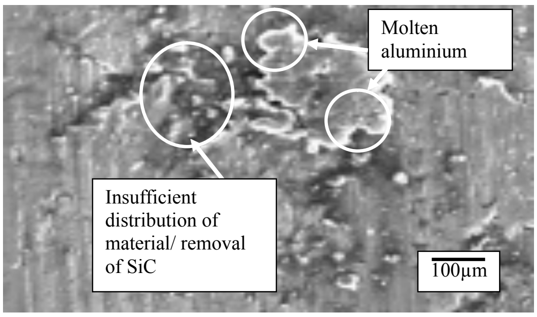
Figure 7 Surface roughness contours in velocity- feed planes at depth of cut of (a) 0.5 mm, (b) 1.0 mm and (c) 1.5 mm



a) Cutting speed = 125 m/min; depth of cut = 1 mm and feed =0.1 mm/rev



b) Cutting speed = 125 m/min; depth of cut = 1 mm and feed =0.2 mm/rev

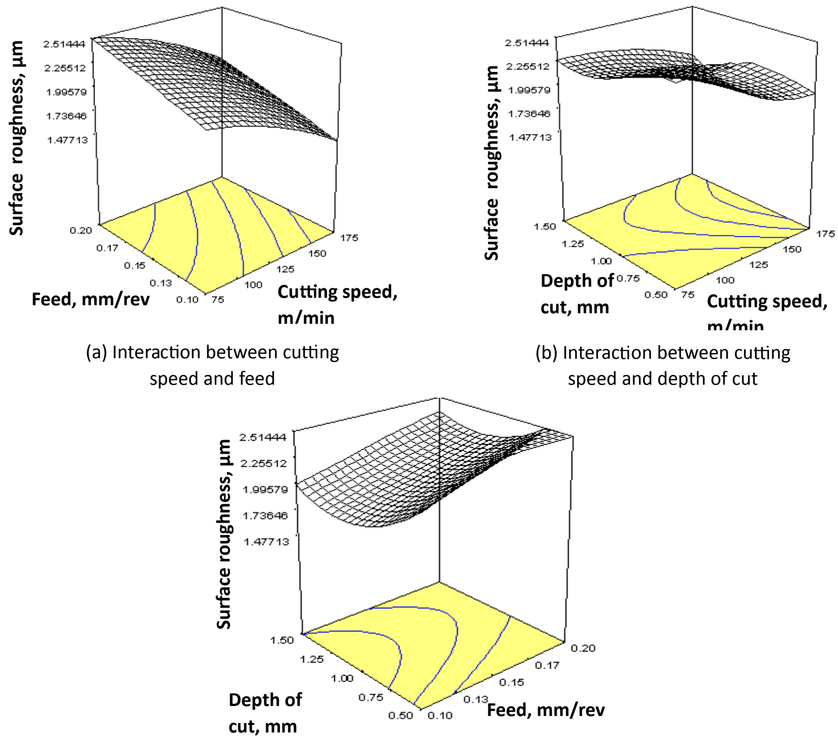


c) Cutting speed = 125 m/min; depth of cut = 1 mm and feed =0.3 mm/rev

Figure 8 SEM micrograph of surface observed in machining of hybrid MMC composites

In the event of turning, the hard ceramics in the workpiece have alternatively contacted with cutting tool, which acts as hard cutters, which affects the performance of the tool. In this connection, the SiC particles play a role of an abrasive substance in between cutting tool and workpiece, this cause high tool wear, imperfection on the surface and also dominant forces. These high forces and tool wear are to be reduced by the addition of fewer amounts of graphite particles. In the act of machining of A1/SiC no other tool performs as well as PCD tools. In the event of machining, the particles are moved over by the tool, which causes the tool breakage. The mechanism of chip formation in the act of A1/SiC-Gr composites differs from ordinary materials, which produces discontinuous chips. The SEM images of the surface profiles observed with reference to the different feed are shown in Fig. 8.

Fig. 9 shows the 3-D response graph with reference to two varying cutting parameters subsequently, the other variable is at unchanging level. Fig. 9 (a) exhibits the interaction between cutting speed and feed. The figure exhibits that, the increase of speed reduces the surface finish and vice versa. During machining, in the event of increasing feed, the normal loads on the tool on the rake face also increase and it generates a heat, by which the surface roughness is also increased in turn. Fig. 9(b) exhibits interaction of cutting speed with deepness of cut by having kept feed at middle level, and hence, there is no considerable difference in surface in surface finishes by varying the depth of cut in hybrid MMC.



(a) Interaction between cutting speed and feed

(b) Interaction between cutting speed and depth of cut

(c) Interaction between feed and depth of cut

Figure 9 3-D response graph for surface roughness

From the figure, it is exhibited that, there is a good finish which is attained at middle level of depth of cut, as it is in opposition to the results which is previously presented [8]. It may be because of in-house fabrication process, the material used inhomogenity, machine tool arrangement, vibration occurred on the machine tool, cutting tool used etc. Figure 9(c) shows the 3-D graph by differing parameters feed and depth of cut, which exhibits the same result as discussed earlier.

The exactness arising from the developed model is carefully verified through confirmation experiments. The confirmation experiment result is shown in Fig. 10.

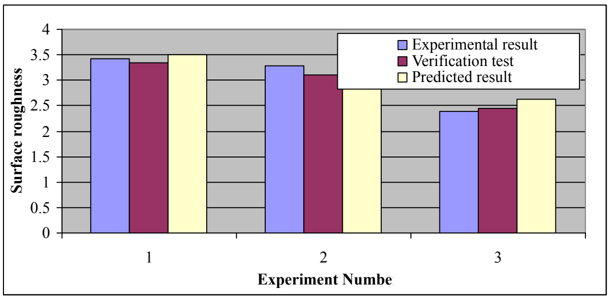


Figure 10 Confirmation test results

The test condition in connection with confirmation test has been selected based on the previous experiments (Experiment No. 7; 16 and 25). The foretold value and observed results have been compared and the error has been obtained. The error observed is within the limits permitted. And hence, the response surface equation is used successfully to foretell the values for any combination parameters, which is considered within the experimental range.

4. Conclusion

1. The quadratic model for surface roughness of Al/SiC-Gr-MMC hybrid composites is developed by means of response surface methodology. The R-Sq. (0.9014) values indicate that, the model is adequate, since Prob $>$ F is $<$ 0.0001.

2. Feed is the important parameter having good influence on the quality, which is followed by cutting speed.

3. The square effect of depth of cut (d^2) and interaction between cutting speed and depth of cut *(V*d)* also have more influence.

4. The surface roughness and feed rate increase simultaneously, but decrease in the event has increasing the cutting speed. The depth of cut does not exhibit definite change.

5. The values, predicted and measured are adequately close to each other, which clearly indicate that the model is elaborately and effectively used for evaluating the surface roughness in machining of hybrid composites.

The result presented in this paper is valid only for the fabricated MMC hybrid composites, but it differs with variation in matrix proportion, graphite content, or other parameters.

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