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EFFECT OF PROCESS PARAMETERS ON MATERIAL REMOVAL RATE DURING MACHINING OF Al-SiC-Gr COMPOSITES

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ABSTRACT

Metal matrix composites have found broad application in industrial fields where parts are required to be light and heat-resistant or wear-resistant properties. Machining of Al-SiC-Gr has become increasingly important in many engineering industry subsequently the prediction of material removal rate is also a significant response in turning conditions. In this experimental study, turning operation was carried out on all gear lathe using carbide cutting tool on Al-SiC-Gr composites and its material removal rate was measured by varying the process parameters. The parameters considered were: combined equal weight fraction of SiC-Gr particulates, cutting speed, depth of cut and feed rate. The central composite design had been utilized to plan the experiments and response surface methodology (RSM) was employed for developing experimental model. Analysis on machining characteristics of Al-SiC-Gr hybrid composites was made based on the developed model.

Keywords: *Al-SiC-Gr Composites, Turning, Material Removal Rate, RSM and ANOVA.*

1. Introduction

The metal matrix composites (MMCs) are being used to replace conventional materials in many applications, especially in the automobile and recreational industries, owing to increasing performance requirements. The most popular types of MMCs are aluminium alloys reinforced with ceramic particles. These low cost composites provide higher strength, stiffness and fatigue resistance with a minimal increase in density over the base alloy. The superior mechanical properties achieved by the reinforcements in MMCs, on the other hand, significantly influence their "machinability" [1]. Even though particulate metal matrix composites having excellent mechanical and thermal properties, these materials are very much complicated to machine. The hard reinforcement particles like SiC acts as abrasive medium between cutting tool and work piece finally ensuing in high tool wear, poor surface finish, less material removal rate (MRR) and more power consumption [2]. The machinability of particulate metal matrix composites (PMMCs) is improved by reinforcing the soft particles like graphite (Gr) along with hard ceramic particles [3]. The addition of graphite content in aluminium matrix composites (AMCs) reduces the cutting forces and this has been attributed by the solid lubrication of Gr particulates. During the machining of Al-Gr composites, graphite particles act as a chip breaker which results in discontinuous chips, less tool wear and low power consumption. Al-Si-Gr composites are used for bearings, pistons etc due to the existence of peculiar properties such as self-lubrication, low wear rate and less friction. It also avoids seizing during inadequate liquid lubrication condition which in turn significantly increases the life, reduces the cost and weight of the component [4, 5]. The percentage reinforcement of Gr in Al-Gr composite and SiC in Al-SiC composite is limited to certain level beyond which it is not beneficial to add either Gr or SiC as reinforcement. The use of multiple reinforcements yields hybrid composites which possess better tribological and machniability properties over the composites with single reinforcement [6]. The MRR of the graphite particulate composite is better among the other ceramic particles reinforcement. The increase in combined % reinforcement of SiC and Gr particulates results in decrease in hardness of Al-SiC-Gr hybrid composites. Therefore the machining of Al-SiC-Gr hybrid composites with higher weight fraction of graphite is easy with maximum MRR [7]. Though the many engineering components are manufactured to near net shape through casting and forming process, they subsequently require machining for preferred dimensions, shape and surface texture [8]. Paulo Davim established a correlation between cutting speed, feed and cutting time with tool wear, power required and

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surface roughness in radial turning of Al-SiC composite with PCD tools using ANOVA analysis. He concluded that the feed rate and cutting velocity has the major influence on tool wear and surface finish [9]. Normally the various measures of machinability considered are cutting forces, power consumed, tool life, surface finish, material removal rate etc. The difficulty occurs since the dependence of these factors on a large number of variables such as work material, tool geometry, cutting conditions, machine tool rigidity etc. In this proposed work, the effect of process parameters and their significance on the performance characteristic of MMR is statistically evaluated by RSM and ANOVA.

2. Experimental Procedures

The composites were fabricated from a molten metal of aluminium alloy using an electric induction furnace. The aluminium alloy LM25 was used as the matrix and its composition details are 7%Si, 0.35%Mg, 0.45%Fe, 0.13%Cu, 0.08%Zn, 0.01%Ni, 0.16%Mn, 0.01Pb, 0.05%Ti, Al-balance. The average particle size of SiC and Gr reinforcements used was 25µm and 50µm. The melting process was carried out in a crucible made from graphite. For manufacturing of MMCs, 5 wt.%, 7.5 wt.% and 10 wt.% of SiC-Gr particles were used. The SiC-Gr particles was added and mixed homogeneously in aluminium matrix by continuous mechanical stirring. Figure 1 shows the stir casting setup for production of Al-SiC-Gr hybrid composites. The size of the casting produced was 30mm diameter and 250mm length (Fig. 2).

Fig. 1 Stir Casting Setup

Fig. 2 Al-SiC-Gr Composite Specimen

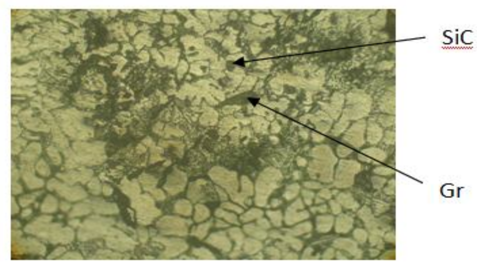

Fig. 3 Microstructure (300x) of Al-5% SiC-Gr Composite

The mechanical properties of aluminium and silicon carbide are very different: young's moduli of 70 and 400 GPa, coefficients of thermal expansion of $24x10^{-6}$ and $4x10^{-6}$ / ^{0}C and yield strengths of 35 and 600 MPa, respectively. By combining these materials of 17% SiC, an MMC with a young's modulus of 96.6 GPa and yield strength of 510 MPa can be produced. The hardness values of Al-SiC-Gr composites decreases from 72 BHN to 66 BHN when the combined SiC-Gr reinforcement increases from 2.5% to 10%. This represents decrease in hardness with increase in % reinforcement of Gr due to increased porosity. The high amount of Gr may result in increase of wear since the fracture toughness decreases with increase in % reinforcement of Gr particulates.

Table 1: Parameters and their Levels used for Turning Operation

Control factors	Levels		
	-1	**0**	**1**
Cutting speed A (m/min)	33	73	113
Feed rate B (mm/rev)	0.25	0.32	0.39
Depth of cut C (mm)	0.2	0.5	0.8
Combined equal weight fraction of SiC-Gr, D (%)	5	7.5	10

Table 2: Experimental Design and Output Response

S. No	Input process parameters								MRR gm/min
	Coded value				Actual value				
	A	B	C	D	A	B	C	D	
1	0	0	-1	0	73	0.32	0.2	7.5	19.45
2	0	0	0	-1	73	0.32	0.5	5	16.37
3	0	0	0	0	73	0.32	0.5	7.5	20.41
4	0	0	0	0	73	0.32	0.5	7.5	20.52
5	0	0	0	0	73	0.32	0.5	7.5	19.97
6	0	0	0	0	73	0.32	0.5	7.5	19.52
7	-1	-1	-1	1	33	0.25	0.2	10	4.25
8	1	-1	1	1	113	0.25	0.8	10	21.57
9	-1	1	1	1	33	0.39	0.8	10	17.99
10	-1	-1	1	1	33	0.25	0.8	10	11.99
11	1	-1	-1	1	113	0.25	0.2	10	13.52
12	1	1	-1	-1	113	0.39	0.2	5	23.17
13	-1	-1	1	-1	33	0.25	0.8	5	6.82
14	0	1	0	0	73	0.39	0.5	7.5	25.61
15	-1	1	1	-1	33	0.39	0.8	5	12.23
16	0	0	0	0	73	0.32	0.5	7.5	20.57
17	0	0	1	0	73	0.32	0.8	7.5	28.01
18	1	1	1	1	113	0.39	0.8	10	35.16
19	0	0	0	0	73	0.32	0.5	7.5	20.45
20	1	1	-1	1	113	0.39	0.2	10	25.2
21	-1	-1	-1	-1	33	0.25	0.2	5	1.21
22	0	0	0	0	73	0.32	0.5	7.5	20.12
23	1	-1	-1	-1	113	0.25	0.2	5	9.52
24	-1	1	-1	1	33	0.39	0.2	10	11.85
25	1	0	0	0	113	0.32	0.5	7.5	22.68
26	-1	1	-1	-1	33	0.39	0.2	5	9.51
27	0	-1	0	0	73	0.25	0.5	7.5	16.43
28	-1	0	0	0	33	0.32	0.5	7.5	8.14
29	0	0	0	1	73	0.32	0.5	10	19.58
30	1	1	1	-1	113	0.39	0.8	5	30.52
31	1	-1	1	-1	113	0.25	0.8	5	21.73

The machining experiments were performed on All gear lathe machine with a maximum speed of 1200 rpm and a 6 KW drive motor. The tool holder ISO 6 L 12 12 K20 and tungsten carbide tool insert DCMT 31 52 MF were used to turn the hybrid composite rods. The experimental parameters and their levels chosen are given in Table 1. The experiments are planned based on Central Composites Design (CCD) scheme of Design of Experiments (DOE). The experimental design having K factors with each factor at two levels is called two level factorial design, provides a linear relationship exists between the factors and the response. Three or higher level experiments are mandatory when nonlinear relationship exists, which ends up with increased cost and time of testing. CCD is most efficient experimental technique, alternative to 3^k or more factorial experimental designs [10]. Table 2 presents the experimental plan and the experimental results obtained. The MRR was determined from the amount of material worn during the period of machining in minutes [11],

$$MRR = (W_i - W_f) / t \quad (1)$$

Where, W_i is the initial weight of work piece in gm; W_f is the final weight of work piece in gm; t is the machining time in minutes. The high precision digital balance meter was used for weighing the samples, thereby eliminating the possibility of errors while calculating the MRR in machining operation.

3. Mathematical Modeling

If all variables are assumed to be measurable, the response surface can be expressed as follows:

$$Y_u = f(A+B+C+D……..+n) \pm \varepsilon \quad (2)$$

Where, Y_u is the corresponding response function (or response surface), A, B, C, D…n are coded values of the process parameters and ε is the fitting error of the u^{th} observations. In this study, for four variables are under consideration, a second-order polynomial regression model, which is called quadratic model, is proposed. The quadratic model of Y_u can be written as follows [12]:

$$Y_u = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{j>i}^{k} b_{ij} X_i X_j + \sum_{i=1}^{k} b_{ii} X_i^2 \pm \varepsilon \quad (3)$$

The coefficient b_0 is the free term, the coefficients b_i are the linear terms, the coefficients b_{ij} are the interaction terms and the coefficients b_{ii} are the quadratic terms. Using the results presented in Tables 2, the full form of the derived models can be presented.

The adequacy of the model is verified using the analysis of variance (ANOVA). The relative significance of the parameters cutting speed (A), feed rate (B), depth of cut (C) and combined % reinforcement (D) on the response variable MRR is statistically analyzed. In Table 3, SS represents sum of squares, DF represents the number of degrees of freedom. The column corresponding to MS is obtained by dividing SS by its corresponding DF. The F column value is the quotient of MS of each effect and MS corresponding to the residual.

The model has been developed for 95% level of confidence. It can be noticed that the MRR model Table 3, an F value of 154.90 implies that the model is significant. The high P value of lack of fit indicates that the model is fit while P value of the model zero, confirms that the model is significant.

Values of "Prob > F" less than 0.0500 indicate model terms are significant. Values greater than 0.1000 indicate the model terms are not significant. From the F and P values, it is observed that the factors A, B, C, D, A^2, C^2, D^2, AB, AC are most influential on MRR.

Table 3: Analysis of Variance for MRR

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	1732.82	1732.82	123.773	154.90	0.0
Linear	4	1491.21	1491.21	372.803	466.55	0.0
A	1	259.46	259.46	259.464	324.71	0.0
B	1	393.87	393.87	393.869	492.91	0.0
C	1	787.78	787.78	787.780	985.88	0.0
D	1	50.10	50.10	50.100	62.70	0.0
Square	4	193.83	193.83	48.457	60.64	0.0
A*A	1	159.13	70.59	70.589	88.34	0.0
B*B	1	1.20	0.40	0.404	0.51	0.5
C*C	1	15.27	25.01	25.014	31.30	0.0
D*D	1	18.23	18.23	18.230	22.81	0.0
Interaction	6	47.78	47.78	7.963	9.97	0.0
A*B	1	26.01	26.01	26.010	32.55	0.0
A*C	1	14.75	14.75	14.746	18.45	0.0
A*D	1	2.10	2.10	2.103	2.63	0.1
B*C	1	3.46	3.46	3.460	4.33	0.1
B*D	1	0.46	0.46	0.462	0.58	0.5
D*D	1	1.00	1.00	1.000	1.25	0.3
Residual Error	16	12.78	12.78	0.799		
Lack-of-Fit	10	11.92	11.92	1.192	8.28	0.2
Pure Error	6	0.86	0.86	0.144		
Total	30	1745.61				

S = 0.893902, PRESS = 93.1238, R-Sq = 99.27%, R-Sq(pred) = 94.67%, R-Sq(adj) = 98.63%

From the above analysis and after eliminating the non significant terms, the final response equation for MRR is given as:

$$MRR = 17.49 - 3.93A + 4.36B + 6.15C + 1.69D - 3.44AC + 0.39A^2 + 2.25C^2 + 1.00D^2 \quad (4)$$

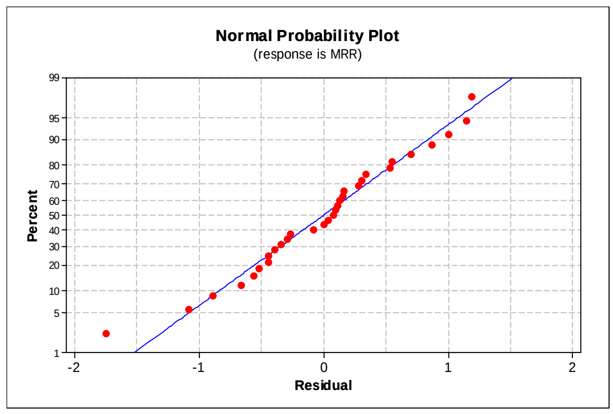

Fig. 4 Normal Plot of Residuals for MRR

The ANOVA for MRR indicated that the model, Eqs.4 was highly significant and adequate to represent the actual relationship between the input parameters and response. Additionally, the developed response surface models for MRR have been checked using residual analysis. The residual plot for response parameter MRR is shown in Fig. 4. In normal plots of residuals, the data are spread approximately in a straight line, which show a good correlation between experimental and predicted values.

4. Parametric Influences and Analysis

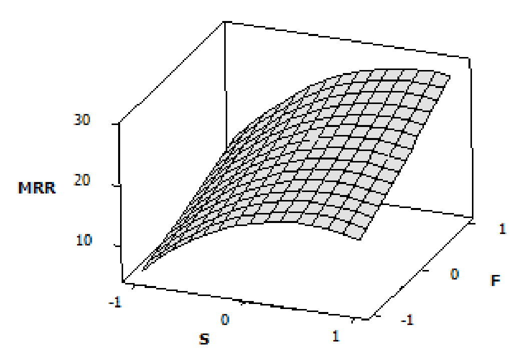

Fig. 5 Surface Plot Showing the Effect of Cutting Speed – Feed Rate on MRR during 0.5 mm Depth of Cut and 7.5 % SiC-Gr.

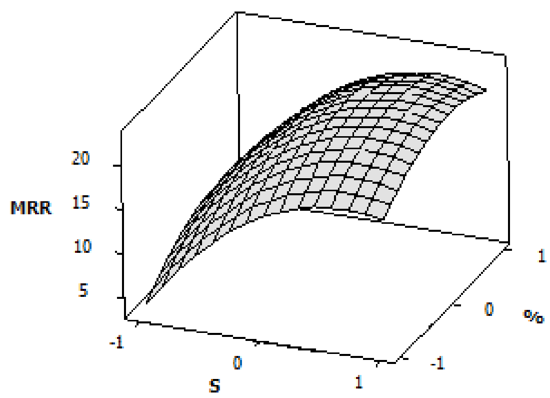

Fig. 6 Surface Plot Showing the Effect of Cutting Speed – % of SiC-Gr on MRR during 0.5 mm Depth of Cut and 0.32 mm/rev Feed Rate.

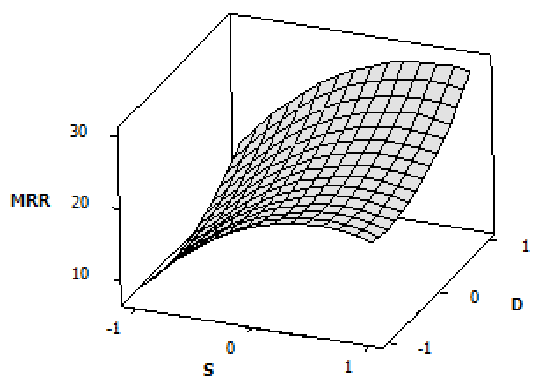

Fig. 7 Surface Plot Showing the Effect of Cutting Speed – Depth of Cut on MRR during 0.32 mm/rev Feed Rate and 7.5 % SiC-Gr.

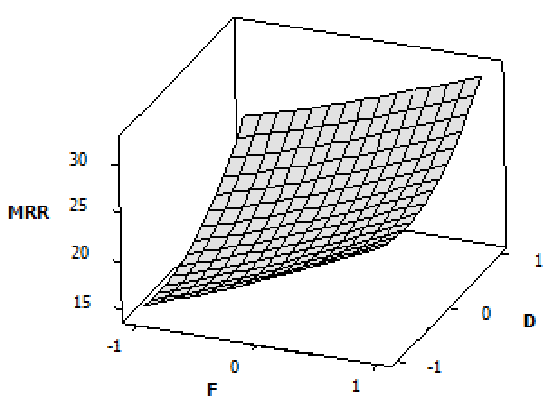

Fig. 8 Surface Plot Showing the Effect of Feed Rate – Depth of Cut on MRR during 73 mm/min Cutting Speed and 7.5 % SiC-Gr.

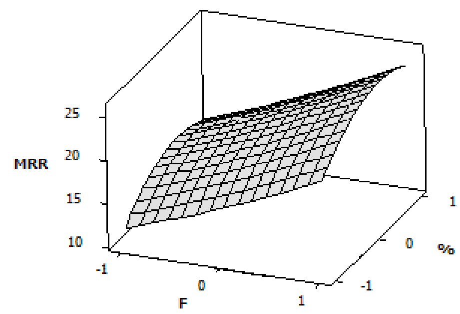

Fig. 9 Surface Plot Showing the Effect of Feed Rate – % of SiC-Gr on MRR during 73 mm/min Cutting Speed and 0.5 mm Depth of Cut.

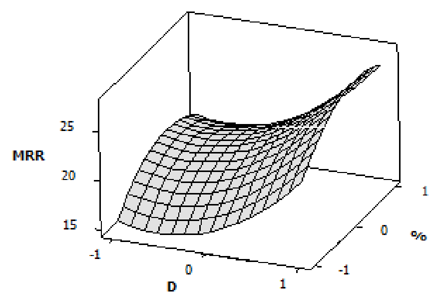

Fig. 10 Surface plot showing the effect of depth of cut – % of SiC-Gr on MRR during 73 mm/min cutting speed and 0.32 mm/rev feed rate.

The parametric analysis has been carried out to study the influences of the input process parameters such as cutting speed, feed rate, depth of cut and combined SiC-Gr % reinforcement on MRR during turning of hybrid composites. Three-dimensional response surface plots were developed based on the RSM quadratic models to assess the variation of response surface. These plots can also indicate the relationship between the input process parameters and response. MRR in is an important factor because of its vital effect on machining characteristics of the material. The surface plot Fig. 5 revels that the combination of higher feed rate and moderate cutting speed leads to larger MRR. The linear nature of variation of the MRR with the feed rate has been observed. The effects of cutting speed and % reinforcement on MRR, while keeping the other parameter at centre level, are shown in surface plot Fig. 6. The MRR increases with the increase of cutting speed up to a certain level and after that it has less effect. From the surface plot, it is found that the % reinforcement has an effect on MRR. The MRR increases with the increase of SiC-Gr % reinforcement.

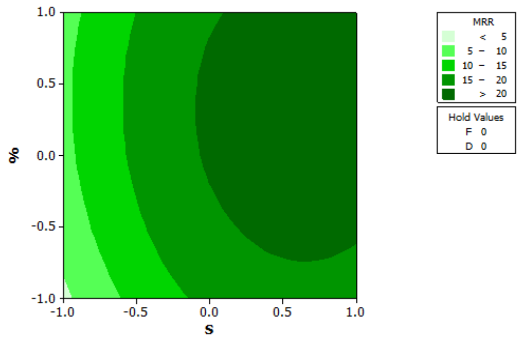

Fig. 11 Contour Plot Showing the Effect of Cutting Speed and % of SiC-Gr on MRR

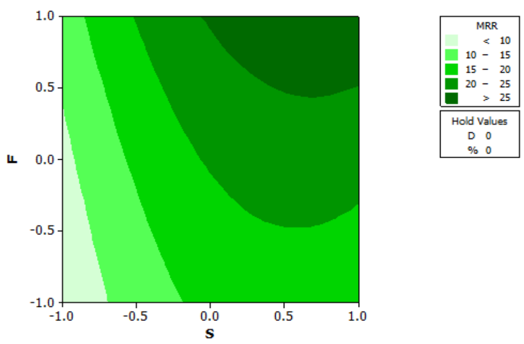

Fig. 12 Contour Plot Showing the Effect of Cutting Speed and Feed Rate on MRR

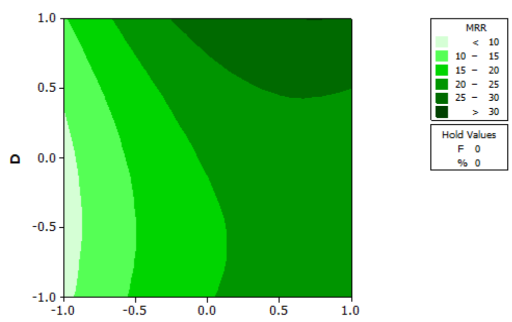

Fig. 13 Contour Plot Showing the Effect of Cutting Speed and Depth of Cut on MRR

The machining of Al-SiC-Gr hybrid composites with higher weight fraction of graphite is easy with maximum MRR and less tool wear. Based on the RSM model, the effects of cutting speed and depth of cut on MRR, while keeping the other parameter at centre level, are shown in Fig. 7. Moreover, it can be clearly seen that an increase in depth of cut leads to a sharp increase in MRR. The surface plots with different combinations of parameters on MRR are shown in Fig. 8 – 10. From the ANOVA of MRR (Table 3), it can be observed that the influence of depth of cut on MRR is more compared to the other parameters. Hence, depth of cut is the most significant input parameter affecting MRR, followed by feed rate, cutting speed and then by combined SiC-Gr % reinforcement. Consequently, it can be concluded that MRR of Al–SiC–Gr are found to be more sensitive to depth of cut and feed rate. The contour plots Fig. 11-16 shows the parametric influences on MRR. The contour plots indicates that the MRR is minimum at low levels of cutting speed, feed rate, depth of cut and combined SiC-Gr reinforcement.

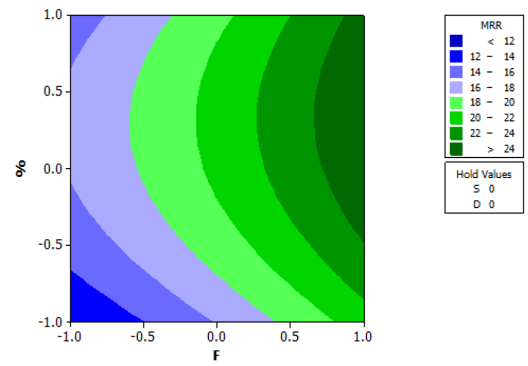

Fig. 14 Contour Plot Showing the Effect of Feed Rate and % of SiC-Gr on MRR

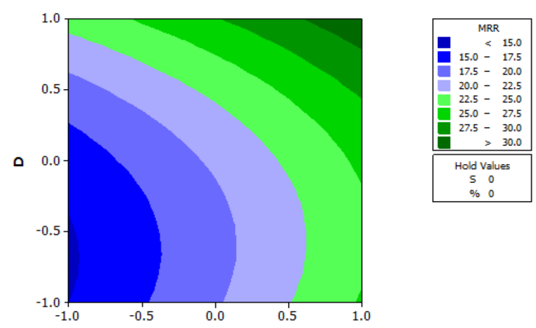

Fig. 15 Contour Plot Showing the Effect of Feed Rate and Depth of Cut on MRR

The effects of speed and % reinforcement are shown in Fig. 11. The combination of low % reinforcement and low cutting speed leads to less MRR. It is evident that the MRR of Al–SiC–Gr hybrid composites increase with increase in combined SiC-Gr reinforcement. Since the hardness values of Al-SiC-Gr composites decreases when the combined SiC-Gr reinforcement increases. It is clear from the contour plot fig. 12 & 14; the change in feed rate plays an important role in achieving high MRR. From the contour plots Fig. 15 & 16, it is found that increase in depth of cut leads to an increase in penetration on tool on the work piece, which is subjected to increase in material removal rate of the work piece.

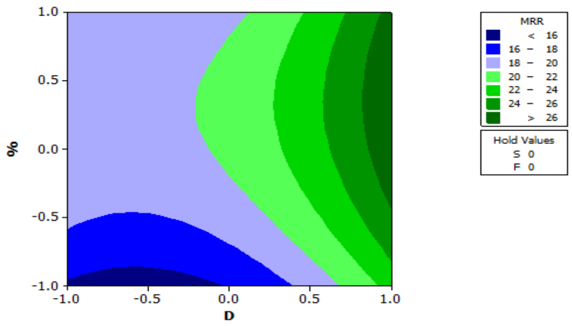

Fig. 16 Contour Plot Showing the Effect of Depth of Cut and % of SiC-Gr on MRR

5. Conclusions

In this study, the MRR in turning of Al-SiC-Gr hybrid composites was modeled and analyzed through RSM.

i. Statistical model have been developed for MRR using central composite design of 31 experiments with three levels of parameters.
ii. The major influence of the parameters based on Analysis of variance towards material removal rate is depth of cut and followed by feed rate, cutting speed and combined equal weight fraction of SiC-Gr particulates.
iii. The material removal rate is better when the depth of cut and feed rate is at high level.
iv. The increase in % of SiC results in increase in hardness of Al-SiC composites. The higher % of SiC induces more flank wear of the tool and simultaneously offers less material removal rate.
v. The machining of 10% combined SiC-Gr specimen offers better MRR since the higher weight fraction of graphite is easy to machine with maximum MRR and less tool wear.
vi. The preferred level of parameters setting in machining of Al-SiC-Gr composites for maximum MRR from the response plots are 73 m/min of cutting speed (level 2), 0.39 mm/rev of feed rate (level 3), 0.8 mm of depth of cut (level 3) and 10% combined equal weight fraction of SiC-Gr reinforcement (level 3).

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