Indian Journal of Science and Technology, *Vol 7(S6), 87–94, October 2014*
ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Experimental Investigation and Analysis of Torque in Drilling Al–15%SiC–4% Graphite Metal Matrix Composites using Response Surface Methodology

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Abstract

This paper presents an experimental investigation on torque in drilling of aluminium hybrid metal matrix composite (Al-15%SiC-4%Gr). The drilling parameters used here was spindle speed, feed rate, drill diameter for 3 levels. The optimized parameter of aluminium hybrid composite was found by taguchi's L_{27} orthogonal array experimentation. The significant parameter was found by ANOVA method. Minitab software has been used for Taguchi's technique. The fabrication technique adopted was stir casting technique. The experiments are conducted on computer numeric control vertical machining centre using multifaceted carbide drills of 4 mm, 8 mm and 12 mm diameter under dry drilling conditions. A response surface analysis is carried out. The effect of drilling parameters on Torque is studied and presented. The results indicated that feed rate is the main parameter which influences the Torque in drilling of hybrid metal matrix Composites.

Keywords: Drilling, Hybrid Metal Matrix Composites, Response Surface Analysis, Torque Measurement

1. Introduction

The aluminium alloy reinforced composites rapidly replace the conventional materials in various industries like aerospace, marine, and automotive. The common applications are bearings, cylinder block linears, vehicle drive shafts, automotive pistons, bicycle frames, etc.[1–3]. 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-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]. Suresha et al.[6] have studied 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 to possess better tribological properties over the composites with single reinforcement.

Davim[7] studied the drilling of metal matrix composites to find the effect of drilling parameters on tool wear, torque and surface finish using Taguchi technique. Jinfeng Leng et al.[8] investigated the machinability of Particulate Metal Matrix Composites (PMMCs) is improved by reinforcing the soft particles like graphite along with hard ceramic particles. The addition of graphite content in Aluminium Matrix Composites (AMCs) reduces the cutting forces and this has been attributed to the solid lubrication of Gr particulates. Iulianoa et al.[9] studied that the most of the composite materials are molded or formed to near net shape, machining is often required for tolerance and surface integrity control.

Burr formation is less, when multifaceted carbide drill is used when compared to conventional coated carbide drills. Conventional coated carbide drilling is preferred

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in applications that require a good surface finish. Surface roughness value increases with an increase in the feed rate and decreases with an increase in the cutting speed[10].

Reinforcement increases the strength, stiffness and the temperature resistance capacity and lowers the density of the MMC. In order to achieve these properties, the selection of reinforcement material depends on the type of reinforcement, method of production and chemical compatibility with the matrix and the following aspects are to be considered while selecting the reinforcement material - chemical composition, shape, dimensions, and properties as in gradient material and their volume fraction and spatial distribution in the matrix[11]. The turning operation is one of the most basic and versatile machining processes[12]. Particulate – reinforced MMC shows the advantage of isotropic properties and cost-effectiveness. Furthermore, an additional advantage of the particulate- reinforced over the fiber reinforced MMC is that, the most existing processing technique is used for fabrication and finishing of the composites, including hot rolling, hot forging, hot extrusion and machining[13]. Large size particles have a tendency towards fracture whereas; small size particles increase the strength and exhibit superior strength of MMC[14]. In this context, the aim of the present study is to investigate the influence of parameters such as spindle speed, feed rate and drill diameter on torque in of Al-SiC-Gr hybrid composites.

2. Experimental Work

Experimental work includes the selection of material, fabrication process, machining work and optimization by Taguchi's L_{27} orthogonal array.

2.1 Material

Al-SiC-Gr Hybrid MMC work piece having aluminium alloy A6061 as the matrix and containing 15% wt. of silicon carbide particles of 50µm and 4% wt. of Graphite particles of 50 µm.

2.2 Fabrication of Hybrid Metal Matrix Composites

Al/SiC/Gr hybrid metal matrix composite in the form of plate was manufactured at Annamalai University, Chidambaram by stir casting process. The process parameter of stir casting technique are: pouring temperature 800–850°C, stirring speed 300–350 rpm, preheating temperature of silicon carbide 1000°C, preheating temperature of graphite particles 450°C, soaking time of preheated particles 2 hrs, duration of stirring 30 mts. The melt was poured to the pre heated metallic die of required shape to make the Plate of 110mm x110mm x 5 mm size. The chemical composition of aluminium alloy A6061 is shown in Table 1. The Figure1 shows the Al-SiC-Gr hybrid composite specimen.

2.3 Machining Test

Drilling operation was selected. The experimental study was carried out in a multi controlled CNC controlled vertical machining center (VMC ARIX 100) capable of working at a speed up to 5000 rpm.

The selected drilling tool was multifaceted carbide drills for machining Hybrid metal matrix composite material. The torque developed in drilling of metal matrix composite materials is measured by using Kistler Piezoelectric-dynamometer.

Table 1. Chemical composition of Al 6061

Element	Weight percentage
Cromium (Cr)	0.15
Copper (Cu)	0.40
Iron (Fe)	0.7
Magnesium (Mg)	0.80
Manganese (Mn)	0.15
Silicon (Si)	7.00
Titanium (Ti)	0.20
Zinc (Zn)	0.25
Aluminium (Al)	90.35

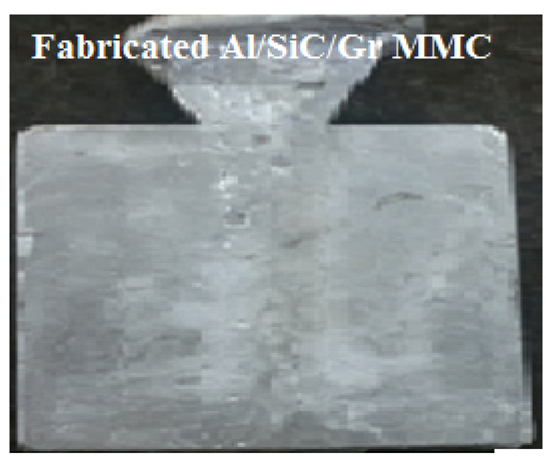


Figure 1. Al-SiC-Gr composite specimen.

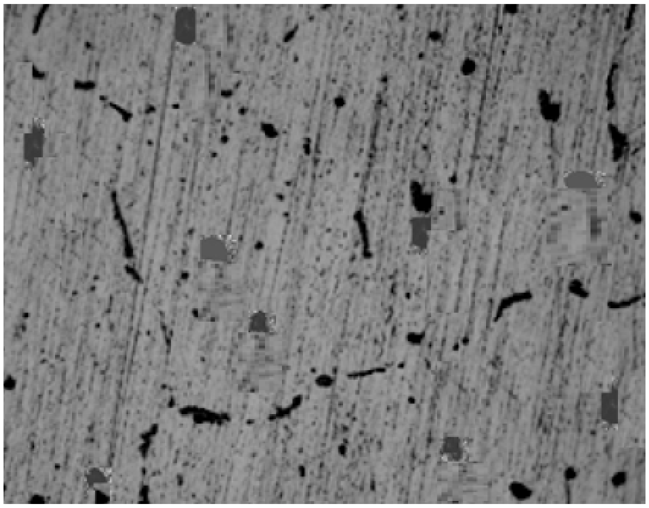


Figure 2. Microstructure of Al-SiC-Gr composite.

The dynamometers form the basic measurement tool in research to measure the components of the cutting forces in machine tool and manufacturing industries. Piezoelectric force measurement system is different from other measurement system in which the quartz crystals are used. The quartz crystals convert the forces into the electric charge. These electric charges are converted to the voltage by means of charge amplifier through the high insulated cable.

The data acquisition and analysis is carried out through the Kistler's DynoWare software. The acquired data is represented graphically in conjunction with the various signals processing functions makes it easier to analyse the torque in Figure 3.

The levels of machining parameter used in the experiment are given in Table 2. The view of the experimental set-up and the multifaceted drill bits is shown in Figure 4.

The torque of each experiment based on L_{27} orthogonal array, Experimental results and its corresponding signal-to-noise (S/N) ratio values is listed in Table 3.

3. Response Surface Analysis for Torque in Drilling of Al/SiC/Gr Hybrid Metal Matrix Composites

Response surface methodology (RSM) is a combination of mathematical and statistical techniques and is used for the development of an adequate functional relationship between a response of interest, y and a number of associated control variables denoted by $x_1, x_2, \ldots, x_k$. RSM uses quantitative data from appropriate experimental designs to determine and simultaneously solve multivariate equations graphically represented as response surfaces which can be used in three ways[15].

Table 2. Machining parameter and their levels

Level	Spindle speed (V = rpm)	Feed rate (f = mm/rev)	Diameter of the drill (d = mm)
1	1000	0.05	4
2	2000	0.10	8
3	3000	0.15	12

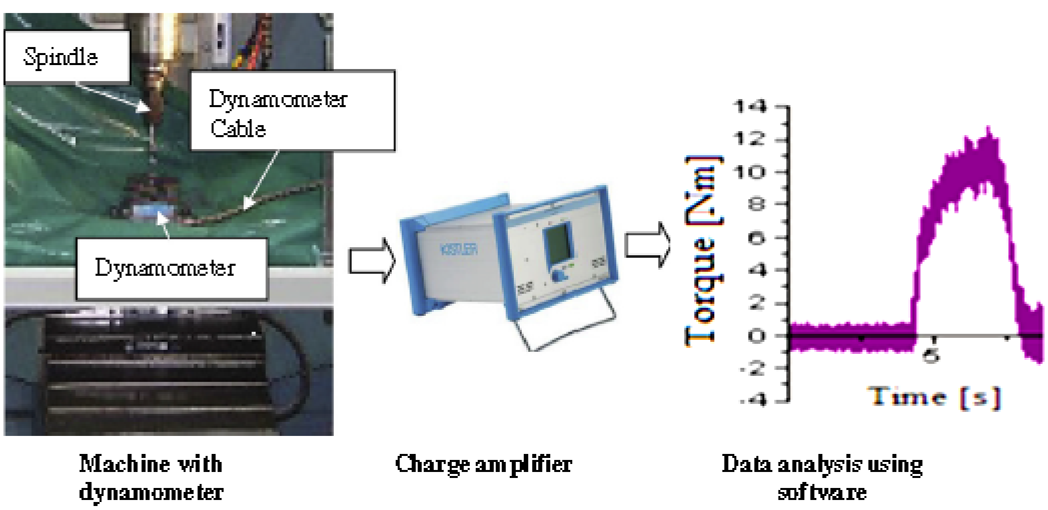


Figure 3. Measurement system used for capturing the Torque in drilling.

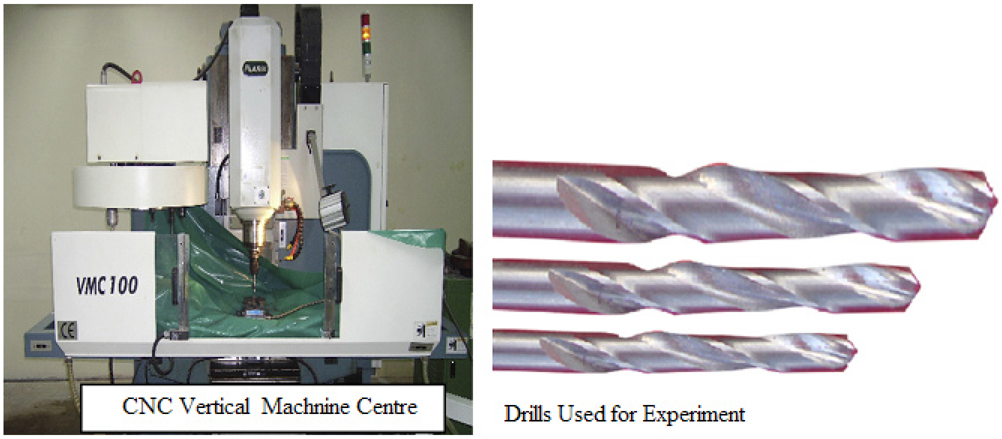


Figure 4. Experimental set-ups and the multifaceted drill bits used for the experiments.

Table 3. Experimental results and its corresponding S/N ratio values

Trial No	Spindle speed V (rpm)	Feed rate f (m/rev)	Diameter d (mm)	Conditions	Torque M_Z (Nm)	S/N ratio (dB)
1	1000	0.05	4	$V_1f_1d_1$	1.81	–0.51
2	1000	0.05	8	$V_1f_1d_2$	2.75	–0.88
3	1000	0.05	12	$V_1f_1d_3$	2.08	–0.64
4	1000	0.10	4	$V_1f_2d_1$	3.07	–0.97
5	1000	0.10	8	$V_1f_2d_2$	3.37	–1.06
6	1000	0.10	12	$V_1f_2d_3$	2.63	–0.84
7	1000	0.15	4	$V_1f_3d_1$	3.54	–1.10
8	1000	0.15	8	$V_1f_3d_2$	3.92	–1.18
9	1000	0.15	12	$V_1f_3d_3$	5.20	–1.43
10	2000	0.05	4	$V_2f_1d_1$	1.27	–0.21
11	2000	0.05	8	$V_2f_1d_2$	1.85	–0.53
12	2000	0.05	12	$V_2f_1d_3$	3.81	–1.16
13	2000	0.10	4	$V_2f_2d_1$	1.98	–0.59
14	2000	0.10	8	$V_2f_2d_2$	2.49	–0.79
15	2000	0.10	12	$V_2f_2d_3$	2.78	–0.89
16	2000	0.15	4	$V_2f_3d_1$	2.57	–0.82
17	2000	0.15	8	$V_2f_3d_2$	3.85	–1.17
18	2000	0.15	12	$V_2f_3d_3$	4.21	–1.25
19	3000	0.05	4	$V_3f_1d_1$	1.12	–0.08
20	3000	0.05	8	$V_3f_1d_2$	1.34	–0.25
21	3000	0.05	12	$V_3f_1d_3$	1.79	–0.51
22	3000	0.10	4	$V_3f_2d_1$	1.39	–0.29
23	3000	0.10	8	$V_3f_2d_2$	1.74	–0.48
24	3000	0.10	12	$V_3f_2d_3$	2.78	–0.88
25	3000	0.15	4	$V_3f_3d_1$	0.97	0.03
26	3000	0.15	8	$V_3f_3d_2$	2.66	–0.85
27	3000	0.15	12	$V_3f_3d_3$	3.07	–0.97

(1) Used to establish the relationship between the input variables and output response for the given settings of control variables.
(2) Used to determine the significance and interrelationships among the input variables considered.
(3) Used to describe the combined effect of all input variables on the response and determine the optimum setting over a certain region of interest.

Response surface methodology is simple and easy to use. In manufacturing systems, the nature of the relationship between y and x values might be known. Then, an equation can be formulated in the form

$$y - f\,(X_1, X_2 .....X_n) + \varepsilon \tag{1}$$

Where '□' represents the noise or error observed in the response 'y'. The expected response be written as:

$$E(y) - f(X_1, X_2 ......X_n) - \eta \tag{2}$$

Then the surface is represented by

$$\eta - f(X_1, X_2 .....X_n) \tag{3}$$

called response surface. In most RSM problems, the form of relationship between the response and the independent variable is unknown. Thus the first step in RSM is to find a suitable approximation for the true functional relationship between y and the set of independent variables is employed. Usually a second order model is utilized in response surface methodology as follows:[16].

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

where 'β' are the coefficients, determined in the second order model using the least square method. In the present work, an empirical relation is developed for correlating the interactive and higher order influences of various machining parameters on surface roughness in machining of Al/SiC/Gr hybrid composites. The model developed for torque in drilling metal matrix hybrid composites is given below:

$$\text{Torque} = 1.1074 + 0.000486111{}^*V + 4.13333{}^*f + 0.0602778{}^*d - 2.43889\text{E-007}{}^*V^2 + 74.4444{}^*$$

$$f^2 - 0.00649306{}^*d^2 - 0.0059500\ V{}^*f + 5.56250\ \text{E} - 005\ V{}^*d + 0.8000f{}^*d$$

The adequacy of the model is checked by using the co-efficient of correlation. The co-efficient of correlation (R – Sq = 92.7%) indicates that the model is adequate at 95% confidence level. Further the analysis of variance is carried out for thrust force in drilling hybrid metal matrix composites.

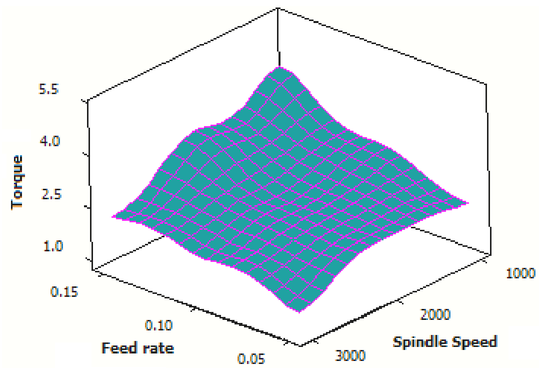
The Analysis of Variance (ANOVA) method is used to evaluate the confidence interval and adequacy of the model. Analysis of variance essentially consists of partitioning the total variation in an experiment into components ascribable to the controlled factors and error.

Table 4 shows the analysis of variance for thrust force. In this table, F-ratio is an index used to check the adequacy of the model in which calculated F-value should be greater than the F-table value. The model is adequate at 95% confidence level since the calculated F-value is greater than the F-table value. From Table 4, the model F-value of 24.03 indicates that the model is significant. The results also indicate that the factors *V, f, d* and the interaction between the factors *V*f* are highly significant in drilling of composite materials when compared to other interactions and square effects considered.

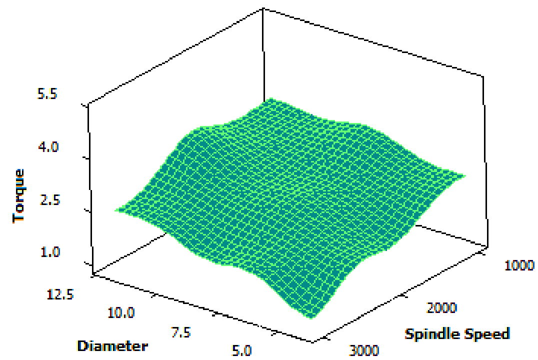
Figure 5 shows the three dimensional response surface for torque in drilling hybrid metal matrix composites. The three dimensional surface plots may provide a clearer picture of the response surface than contour plots. The figure 5 clearly indicates that the low feed rate, high spindle speed and low drill diameter are preferred for the drilling of hybrid metal matrix composites. Songmene and Balazinzki[17] and Basavarajappa et al.[18] reported the effect of graphite in Al/SiCp–Gr composites, according to them inclusion of graphite in the composite has reduced the hardness and strength of the composite. These are favorable for machinability. In the present case the reduction in torque, when drilling graphitic composites can also be observed, this property indicates the positive effect of the graphite in the composite. This may be due to the natural lubricant property of the reinforcement which eases the machining[19].

Table 4. Model summary statistics for torque

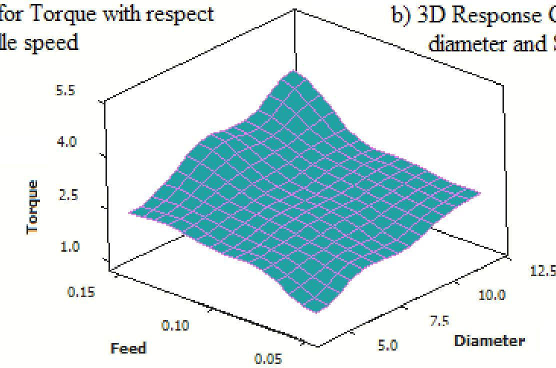
Source	Degree of freedom	Sum of square	Mean square	F-Value	P (%)
V	2	6.360	3.18	4.556	21.89
f	2	7.228	3.614	5.178	24.88
d	2	5.277	2.613	3.744	18.16
V f*	4	2.062	0.515	0.734	7.10
V d*	4	1.573	0.393	0.563	5.42
f d*	4	0.959	0.234	0.335	3.31
Error	8	5.589	0.698		19.24
Total	26	29.048			100



a) 3D Response Graph for Torque with respect to feed rate and spindle speed



b) 3D Response Graph for Torque with repect to diameter and Spindle speed



c) 3D Response Graph for Torque with respect to feed and diameter

Figure 5. Three dimensional response surface graph for Torque.

4. Optimum Machining Conditions

Table 5 shows the taguchi response table for S/N ratio values of torque. The response table was determined to find out the optimum factors which influence the surface roughness. The data in the response table was obtained by the average sum S/N ratio values as per the corresponding factor and the level in each column of orthogonal array.

The optimum machining conditions for the spindle speed, feed rate, and drill diameter are determined as 3000 rpm, 0.05 mm/rev and 4 mm respectively. Table 6 shows the optimal process parameter values for Torque using Multifaceted drill.

Table 5. Taguchi response table for S/N ratio values of torque

Level	Spindle speed (A)	Feed rate (B)	Diameter (C)
1	– 9.574	– 5.325*	– 5.074*
2	– 8.241	– 7.554	– 8.004
3	– 4.790*	– 9.726	– 9.527
Delta	4.783	4.401	4.454
Rank	1	3	2

Table 6. Optimal process parameter values for Torque using Multifaceted drill

Process parameter	Levels	S/N response value
Spindle Speed (A)	3	– 4.790
Feed rate (B)	1	– 5.325
Diameter (C)	1	– 5.074
Optimal condition $A_3B_1C_1$		

5. Confirmation Experiments

Confirmation experiments are carried out to assess the reliability of the models developed against the experimental results. The parameters for confirmation experiments are selected based on the experimental condition and the process parameters setting other than the experimental conditions used in the table. The drilling conditions selected for confirmation experiments are provided in Table 7. The responses resulting from confirmation experiments are given in Table 8.

The Scanning electronic micrograph image in Figure 6 shows the huge pockmark feature disappears since the surfaces were machined under optimized process parameter sets ($A_3B_1C_1$). The surface defects such as globules debris, cracks disappear except crater scattering.

Table 7. Drilling conditions for confirmation experiments

Cutting tool	Experiment No.	Spindle speed (rpm)	Feed rate (mm/rev)	Diameter (mm)
Multifaceted drill	1	2000	0.05	8
	2	2500	0.075	12
	3	3000	0.10	12

Table 8. Response parameters obtained for confirmation experiments

Cutting tool	Experiment No	Model	Torque
Multifaceted Drill	1	Experiment	1.85
	2	RSM	1.81
	3	Experiment	4.85
	4	RSM	4.71
	5	Experiment	2.78
	6	RSM	2.49

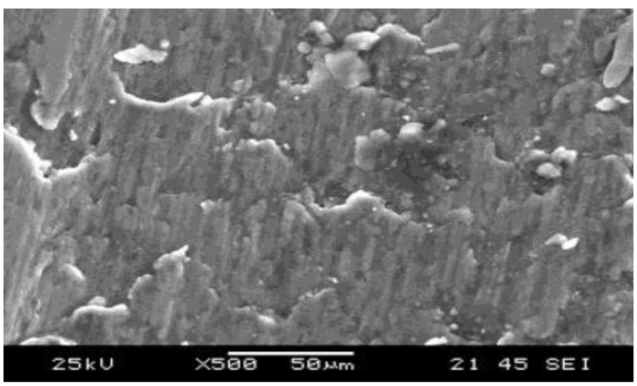


Figure 6. SEM image of machined surface at optimum machining Conditions ($A_3B_1C_1$).

6. Conclusion

The following conclusions can be drawn from the present investigation on drilling of Al–15% SiC–4% Graphite hybrid metal matrix composites using Multifaceted carbide drills at different cutting Parameters:

Statistical models have been developed for Torque using L_{27} orthogonal array with three levels of factors. The major influence of the factors based on Analysis of Variance towards Torque is Spindle speed, followed by feed rate and drill diameter. Feed rate is the main factor, which influence the torque in drilling of composite and as the feed rate increases the torque also increases. Torque decreases with increase in spindle speed and vice versa. Torque varies with feed, feed rate affects drilling forces but spindle speed has comparatively less influence than feed rate. Lower speed shows comparatively more Torque than higher spindle speed. The model used in the work is able to predict the torque in drilling of hybrid metal matrix composites, within the ranges of cutting parameters studied. The accuracy of the model can be improved further by adopting more cutting conditions and more variables. Spindle speed is the most influential factor in Torque measurement followed by the diameter and feed rate. The developed mathematical model could be effectively used for predicating the output responses for a given set of input machining parameters. The experimental results have close proximity (95%) to predicted value. It validates the analytical models developed in this work.

7. Scope of Future Work

The number of machining parameters can be extended and hence, the data base can be improved by extensive experimentation. The experimental work can be extended to other machining processes. The effect of process parameters may be assessed by varying the orientation of reinforcement material present in the composite material.

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