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Surface Roughness Prediction by Response Surface Methodology in Milling of Hybrid Aluminium Composites

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Abstract

In the present study, a Response Surface model (RSM) has been developed to predict the surface roughness during face milling of Hybrid composites. Experiments were carried out with tungsten carbide insert at various cutting speed, feed, and weight fraction of Alumina (Al_2O_3). Materials used for the present investigation are Al 6061-aluminum alloy reinforced with Al_2O_3 of size 45 microns and graphite (Gr) of an average size 60 microns, which are produced by stir casting route. Central composite face centered second order response surface methodology was employed to create a mathematical model and the adequacy of the model was verified using analysis of variance. Also a comparison has been done between the result obtained through response surface methodology and experimental values which indicates that the experimental values are very much close to the predicted values.

Keywords Surface roughness; hybrid composites; Response Surface Methodology; Face millingIntroduction

1.Introduction

Metal matrix composites (MMC) are new class of engineering materials which finds its application in automotive, aircraft and defence mainly because of its improved properties than alloys. There are various matrix and reinforcement available out of which aluminium reinforced with ceramics particles either Silicon Carbide (SiC) or Al_2O_3 finds to be important. Ceramics are harder particles which improve the mechanical properties of the composites compared with the base alloy [1, 2]. The hard reinforcement or ceramics particles found in these materials make them difficult to machine and get into required shape. These hard particles not only increases the tool wear but also makes the surface rough. This results in poor tool life and inconsistent part quality and thus limits the use of MMCs in many applications. In order to overcome the above difficulties a small amount of soft reinforcement were added along with the hard

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ceramics to form a hybrid MMC. Graphite aluminium MMC reinforced with alumina is easier to machine than those reinforced with both SiC and graphite or Sic particles only studied by Songmene et al. [3]. Surface roughness of a machined product plays a significant role in determining the quality of the product in today's manufacturing industry. Moreover, surface roughness is an important factor in determining the machinability of materials [4]. The surface condition of a machined part is affected mainly by machining parameters such as cutting speed, feed rate, weight fraction, particle size and depth of cut on the surface roughness for a given machine tool and work piece set-up. The quality of the surface has a very important role in the performance of face milling because a good quality machined surface significantly improves fatigue strength, corrosion resistance and creep life. While there are several ways to describe surface roughness, the average surface roughness (R_a), which is mostly used in industrial environments, is taken-up for the present study. R_a is defined as the arithmetic value of the departure of the profile from centreline along the sampling length. It is defined as:

$$Ra = \frac{1}{l}\int \left| (y) \right| x$$

Where l is the sampling length and y is the ordinate of the profile curve.

The primary objective of manufacturing operation is to efficiently produce parts with high quality. Milling is a widely used machining process in manufacturing in which face milling is a machining process that produces flat surfaces. In order to improve the efficiency of machining process, and to reduce the total machining cost the optimum machining parameter have to be arrived. The setting up of machining parameters relies strongly on the operator's experience. Optimum machining parameters are of great concern in manufacturing environments, where economy of machining operation plays a key role in competitiveness in the market. It is difficult to utilize the highest performance of a machine owing to their being too many adjustable machining parameters [5].

Many researchers have studied the machining characteristics of ceramic reinforced composites. Rajesh et al. [6] reported that Surface roughness of Al alloy is less as compared to Al alloy composite during turning by carbide as well as PCD inserts. Further they recommend Carbide inserts for low speed and PCD for higher speeds for low flank wear. Brown and Surappa [7] studied the machinability during turning of Al/Si/Gr composites and found that the machining forces were considerably reduced for the graphitic composites. The effect of cutting feed and volume fraction of the reinforced particles in drilling of self lubricated $Al/Al_20_3/Gr$ hybrid composites on the thrust force and cutting torque using experimental techniques and ANN was studied by Hayajneh et al .[8]. Kok et al.[9] Studied that the surface roughness value of the K10 tool was higher than that of the TP30 tool. The surface roughness increased with an increase in the cutting speed while it decreased with increasing the size and volume fraction of particles for both tools in all cutting conditions. Also the dependency of the surface roughness on the cutting speed was smaller when the particle size was smaller when drilling $2024Al/Al_2O_3$ particle composites. Palanikumar et al.[10] investigated the factors influencing surface roughness in machining of Al/SiC particulate composites. They have concluded that feed rate is the main factor which influences the surface roughness in machining Al/SiC composites. Lou et al. [11] studied the effect of spindle speed, feed rate, and depth of cut on the surface roughness of the end milling process. They used in-process surface roughness recognition and a neural fuzzy system to predict the work piece surface roughness. Su et al. [12] conducted the Taguchi method in the metal milling experiments to evaluate the flank wear, some variables were selected, including the structure of the coating film, cutting speed, feeding rate, milling depth, hardness of the work piece and types of milling path. An optimal thickness of the TiCN coating film for the Tungsten carbide cutter was determined. Karthikeyan et al.[13] observed that the volume fraction of SiC particles present in the aluminium alloy matrix has a significant effect on the milling characteristics, increasing tool wear and specific energy and decreasing surface roughness. Ramulu et al. [14] conducted experiments by using PCD drills to drill Al_2O_3 particle reinforced aluminium-based metal matrix composites. The ANOVA, response surface methodology was used to analyze experimental data and developed regression models. They concluded that drilling forces and average surface roughness values were greatly influenced by the feed rate than the cutting speed.

Most of the current literatures present experimental results when milling ceramic-reinforced MMCs. However, limited information is available on the milling of graphitic ceramic-reinforced composites. The main objective of the paper is to study the influence of feed rate, speed and alumina weight fraction on surface roughness in face milling of hybrid composites using RSM.

1. Experimental procedure

1.1. Materials and Methods

The aluminium 6061 alloy reinforced with varying weight fraction (5,10,15%) of Alumina particles and constant weight fraction(5%) of graphite particles are fabricated through stir casting method .Thus three types of Specimen were fabricated. The chemical composition of Al 6061 is shown in table.1. Stir casting is the simplest and the most commercial technique. The development of MMCs by stir-casting technology has been one of the unique and feasible processes because of producing better matrix particle bonding, easier control of matrix structure, simplicity, higher production rate, and low cost [15].This process is similar to the fabrication methods used in earlier research [16]. Face milling is conducted on ARIX VMC 100 CNC Vertical machining centre. The experimental setup is shown in the Fig. 1.The tungsten carbide insert and cutter of 16mm diameter is employed. All experiments are performed under dry machining condition. Surface roughness (R_a) was measured using a stylus instrument for a cut off and sampling length of 0.8mm. For each specimen, the mean of five surface roughness measurements were taken.

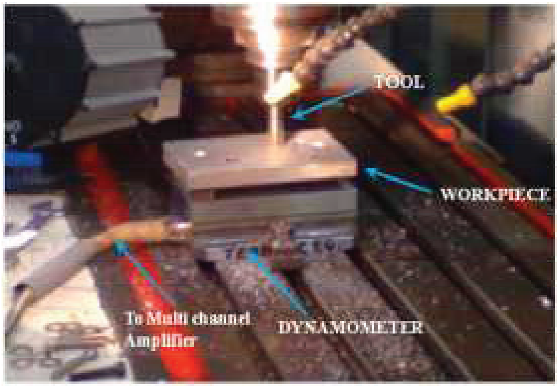

Fig.1. Experimental setup

Table 1 Chemical composition of 6061 Aluminum alloy

Element	Si	Cu	Mg	Mn	Fe	Zn	Sn	Ti	Pb	Al
Wt %	0.80	0.35	0.8	0.02	0.01	0.008	0.01	0.01	0.02	97.9

2.2. *Response Surface Methodology*

Response surface method (RSM) adopts both mathematical and statistical techniques which are useful for the modelling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize the response [17]. The objectives of quality improvement, including reduction of variability and improved process and product performance, can often be accomplished directly using RSM. In the RSM, the quantitative form of relationship between the desired response and independent input variables is represented as follows

$$Y = F\ (f, v, w) \quad (1)$$

Where Y is the desired response and F is the response function and f, v, and w represents Feed rate, speed and weight fraction of Al_2O_3 respectively. In order to study the effect of the process parameters a second order polynomial response surface can be fitted into the following equation.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_i X_i^2 + \sum_i \sum_j \beta_{ij} X_i Y_j + \xi \quad (2)$$

Where, '*Y*' is the corresponding response, and xi is the value of the i^{th} machining process parameter. The terms β are the regression co-efficients, and ξ is the residual measure, resulting from a experimental error in the observations.. This quadratic model works quite well over the entire factor space.

The necessary data required for developing the response models have been collected by designing the experiments based on Central Composites Design (CCD). CCD is the most popular second-order design which was introduced by Box and Wilson. It is a factorial or fractional factorial design with centre points and star points. The test was designed based on a three-factor-three levels central composite design with full replication. A central composite design consisting of 20 experiments was used in the experiments. Table 2 shows the process variables used in the experiments. Central composite design matrix, with actual variables and Experimental values was shown in the table 3.Using analysis of variance (ANOVA), the significance of input parameters is evaluated. Design-Expert 8.0 was used to establish the design matrix, to analyze the experimental data and to fit the experimental data to a second-order polynomial. Sequential F test, lack-of-fit test, and other adequacy measures were used to check the model's performance.

Table 2. Process variables used

Process variables	Notation	Unit	Limits		
			-1	0	+1
Feed rate	f	mm/min	50	100	150
Speed	v	Rpm	1000	2000	3000
Weight of Alumina	w	%	5	10	15

2. Results and Discussions

The RSM was performed to predict the surface roughness in milling of hybrid Al composites. The analysis of variance of the experimental data was done to statistically analyze the relative significance of the machining parameters such as feed rate (f), spindle speed (v), and weight fraction on Alumina (w) on

Table 3. Central composite design matrix, with actual variables and Experimental values

Exp.No	Run order	Feed rate f (mm/min)	Speed v (rpm)	Weight of Alumina w (%)	Experimental values Ra (µm)
1	6	50	1000	5	1.69
2	5	150	1000	5	1.99
3	10	50	3000	5	0.56
4	1	150	3000	5	0.84
5	17	50	1000	15	1.26
6	16	150	1000	15	1.71
7	8	50	3000	15	0.32
8	4	150	3000	15	0.72
9	3	50	2000	10	1.12
10	15	150	2000	10	1.48
11	9	100	1000	10	1.75
12	13	100	3000	10	0.65
13	7	100	2000	5	1.31
14	11	100	2000	15	1.22
15	12	100	2000	10	1.23
16	19	100	2000	10	1.3
17	2	100	2000	10	1.34
18	18	100	2000	10	1.36
19	14	100	2000	10	1.32
20	20	100	2000	10	1.39

response variable surface roughness. From the table 3, model F value of 131.22 indicates that the model is significant for surface roughness. The values of "Prob>F" for model is less than 0.1000 which indicates that the model terms are significant. The "Lack of Fit F-value" of 0.8973 implies the lack of fit is not significant. There is only a 0.01% chance that a "Model F Value" this large could occur due to noise. The R^2 (0.99) value is high, close to 1, which is desirable. From the ANOVA results, it is concluded that the factors f, v, w and their interactions fv and fw have significant effect on surface roughness .The regression equations obtained for the response factors by using multiple regressions is given below.

$$\text{surface roughness} = +1.78991+3.92545E\text{-}003 * f -1.33727E\text{-}004 * v -0.012745 * w -1.75000E\text{-}007 * f * v +1.35000E\text{-}004 * f * w +8.75000E\text{-}006 * v * w -6.72727E\text{-}006 * f^2 -1.16818E\text{-}007 * v^2 -2.07273E\text{-}003 * w^2 \quad (3)$$

The normal probability plots for residuals and the plots of the predicted versus actual values for surface roughness are shown in Figs. 2 and 3. The adequacy of the model was tested through residual analysis table. Figure 1 shows that the residuals fall on a straight line which indicates that the errors are distributed normally with respect to the predicted value. The Relationship between predicted and actual

Table 3.ANOVA Table for surface roughness

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	3.436027	9	0.381781	131.2258	< 0.0001	significant
f-feed rate	0.32041	1	0.32041	110.1315	< 0.0001	
v-speed	2.81961	1	2.81961	969.1577	< 0.0001	
w-weight of Alumina	0.13456	1	0.13456	46.25103	< 0.0001	
Fv	0.000612	1	0.000612	0.210529	0.6562	
Fw	0.009113	1	0.009113	3.132153	0.1072	
Vw	0.015313	1	0.015313	5.26322	0.0447	
f^2	0.000778	1	0.000778	0.26736	0.6164	
v^2	0.037528	1	0.037528	12.89909	0.0049	
w^2	0.007384	1	0.007384	2.538063	0.1422	
Residual	0.029093	10	0.002909			
Lack of Fit	0.01376	5	0.002752	0.897396	0.5458	not significant
Pure Error	0.015333	5	0.003067			
Cor Total	3.46512	19				
R^2						0.99
Adj R^2						0.98

value shown in figure 2, reveals that no obvious pattern and unusual structure and also most of the value are close to the centre line and hence the empirical model provides reliable prediction [18, 19]

From the developed RSM-based mathematical model, the effect of milling parameter on surface roughness is examined.The 3D surface plots are shown in the Figs.4-6. From these figures it is found that the surface roughness is greatly influenced by the speed compared to the other parameters. It is clear from the figures that the surface roughness decreases with the increase of cutting speed and weight fraction of alumina however, it increases with the increase of feed. Similar results are also obtained by Basavarajappa et al. [20]. The cutting speed plays an important role in deciding the surface roughness [21]. At high cutting speeds, the surface roughness decreases. At low speeds, the (built up edge) BUE is formed and also the chip fracture readily producing the rough surface. As the speed increase, the BUE vanishes, chip fracture decreases, and hence the roughness decreases. The increases in feed proportionally increase the surface roughness. The increase of feed increases the normal load on the tool and also generates more heat which in turn increases the surface roughness. The weight fraction of Al_2O_3 particles plays an important role for deciding the surface roughness [13]. The increase in weight fraction of Al_2O_3, decreases the surface roughness. With increase in weight fraction, the rate of decrease in roughness is reduced due to increased brittleness and subsequent disappearance of BUE [22].

In order to predict and verify the surface roughness for milling of Al hybrid composites with respect to the chosen initial parameter setting, confirmation tests are used. Fig. 5 shows the comparison between the experimental values and predicted values. From the figure, its is noticed that the predicted values are very close to the experimental values which indicates that the obtained model is well suited for predicting the surface roughness.

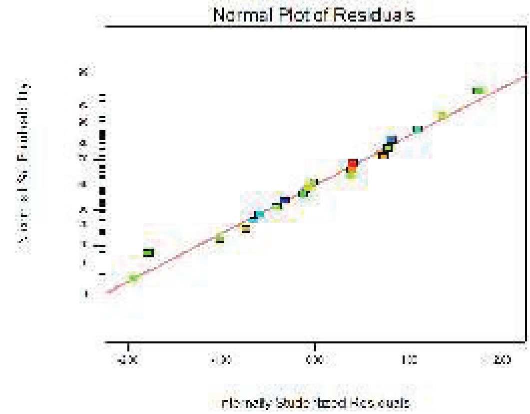

Fig. 2. Normal probability plot for residuals

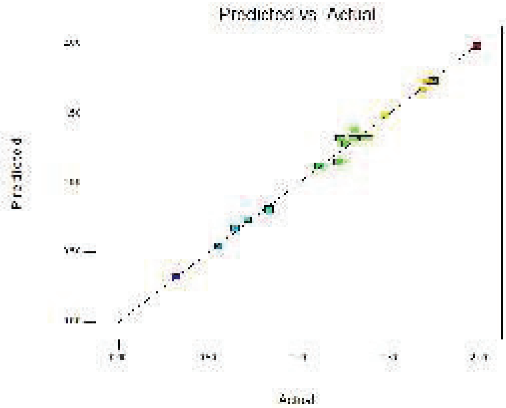

Fig. 3. Predicted Versus actual values

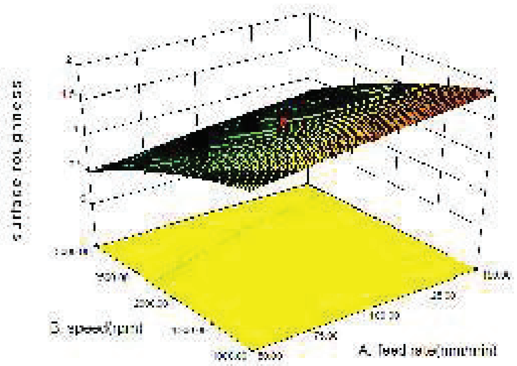

Fig. 4. 3D graph shows the interaction effects of surface roughness on Feed rate Vs Speed

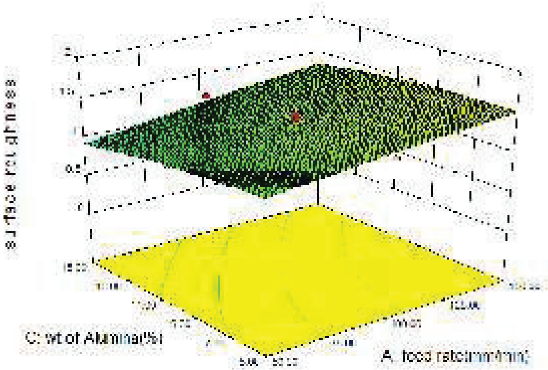

Fig. 5. 3D graph shows the interaction effects of surface roughness on wt of alumina Vs Feed rate

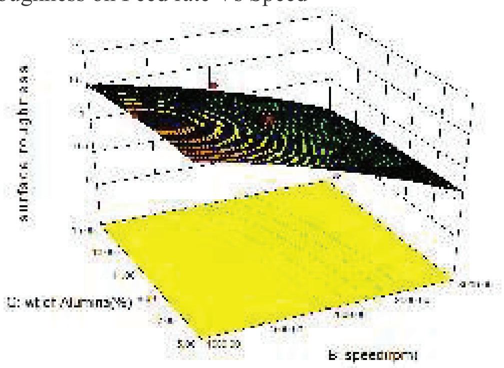

Fig. 6.3D graph shows the interaction effects of surface roughness on wt of alumina Vs speed

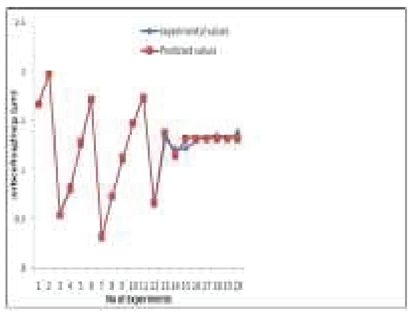

Fig. 7. Comparison between Experimental values and Predicted values

3. Conclusion

The following conclusions are drawn from the experimental results during the milling of Al 6061/ Al_2O_3/Gr composites using tungsten carbide insert under different cutting conditions.

- From the RSM model, the predicted and measured values are quite close, which indicates that the developed model can be effectively used to predict the surface roughness. Using this model, a noticeable saving in time and cost has been obtained to select the level of milling parameters.
- Speed is the major factor, which has more influence on surface roughness, followed by feed rate and weight fraction of Al_2O_3.
- Among the interaction, cutting speed and feed rate has greater influence compared with other interactions on surface roughness on milling of Al Hybrid MMC composites.

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