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Influence of Process Parameters on Machining Al-Sic-Gr Hybrid Composites

P. Suresh[1] and P. Mathiyalagan[2]

[1,2]School of Mechanical Engineering, Galgotias University, Greater Noida, Uttar Pradesh
E-mail: [1]psuresh2730@gmail.com, [2]mathis09051970@yahoo.co.in

Abstract—*Hybrid aluminium composite reinforced with silicon carbide (SiC) and graphite (Gr) facilitate easy machining due to tribological properties of graphite particulates. In this study optimization of process parameters in machining Al-SiC-Gr hybrid composites for individual and multi-response characteristics are studied. The experiments are performed based on Taguchi L18 orthogonal array in all gear lathe using tungsten carbide tool by varying the process parameters such as cutting speed, feed rate, depth of cut and combined equal weight fraction of SiC-Gr. Analysis of variance (ANOVA) is employed to find out the contribution and influence of parameters on the individual response characteristics of surface roughness and material removal rate. The multiple performance characteristics are also analyzed using grey relational approach by determining the grey relational coefficients and grades.*

Keywords*: Hybrid composites; Machining; Surface roughness; Material removal rate; Optimization*

1. INTRODUCTION

Metal matrix composite materials provide interesting opportunities for new product design due to higher specific properties of strength and stiffness, increase in wear resistance, lower coefficient of thermal expansion, dimensional stability at higher temperature when compared to unreinforced monolithic alloys. In aluminium metal matrix composites (AMCs), the matrix phase is aluminium / aluminium alloy and the other constituent is reinforcement generally Gr, SiC, Al_2O_3, B_4C, etc [1, 2]. The addition of graphite content in AMCs reduces the cutting forces and this has been attributed to solid lubrication of Gr particles. During machining of Al-Gr composites, graphite particles act as a chip breaker which results in discontinuous chips, less tool wear and low power consumption [3]. The percentage reinforcement of Gr and SiC particles in aluminium matrix is restricted to certain level; further addition is not beneficial for the composite [4]. Composites with combined reinforcement of SiC and Gr particulates are referred as Al–SiC–Gr hybrid composites. This hybrid composite is alternate materials for pistons, cylinder liners, brake drums in automotive and aerospace fields due to enhanced properties [5, 6]. Paulo Davim established a correlation between cutting speed, feed and cutting time with tool wear, power required and 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 [7]. The need for precise machining of composites are increased in many fields and hence it is necessary to select most appropriate machining conditions in order to reduce manufacturing cost, produce high quality parts and to improve the efficiency. In this proposed work, the effect of process parameters and their level of significance on the individual performance characteristics of surface roughness (Ra) and material removal rate (MMR) are statistically evaluated by ANOVA. In addition, grey relational analysis is also used to optimize the parameters for multi performance characteristics of minimum surface roughness and maximum material removal rate in machining of Al-SiC-Gr hybrid composites.

2. EXPERIMENTAL PROCEDURE

2.1. Materials

The matrix material used is aluminium alloy LM25 contains silicon content between 7 to 15% which will inhibit the formation of reaction product Al_4C_3 from SiC. The chemical composition of LM25 aluminium alloy is 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 reinforcements used are silicon carbide and graphite particles. The silicon carbide particles are exhibited in the form of solid crystal where as graphite particles in the form of flakes. In this work, Al-SiC-Gr hybrid composites required for investigation are produced from LM25 aluminium alloy with 5, 7.5 and 10% of combined equal weight fraction of SiC-Gr particles.

2.2. Production of Hybrid Composites

The SiC and Gr particles were kept in muffle furnace and retained at 900^0C for 3 hours. The preheating process develops oxidation layer around SiC particle which will avoid the detrimental reaction product Al_4C_3, but the graphite particles are relatively stable at high temperature. The aluminum alloy was heated to 800^0C in a graphite crucible and the melt was degassed and cleaned. By using stir casting technology, SiC and graphite particles were added and mixed homogeneously in Al alloy matrix by mechanical stirring. The molten slurry was poured into the steel die and allowed to solidify. The size of the casting produced is 30mm in diameter and 250mm in length. Al-SiC-Gr hybrid composite specimens with 5, 7.5 and 10% of combined equal weight fraction of SiC-Gr particles is shown in Figure 1.

Fig. 1: Al-SiC-Gr hybrid composite specimens with 5%, 7.5% and 10% of SiC-Gr particles

2.3. Machining Details

The experimental work was carried out on All Gear Lathe and its maximum spindle speed is 1500 rpm. The tool holder MTJNL 2525M16 and tungsten carbide tool insert TNMG 120408 were used for machining the hybrid composite rods. HSS tools are incapable of machining with Al-SiC-Gr hybrid composites. Hence, tungsten carbide tools are chosen for rough machining in order to reduce the machining cost and PCD tools could be preferred to finish machining operations [8]. The experimental parameters and their levels chosen for L_{18} orthogonal array are given in Table 1.

Table 1: Parameters and their levels of L_{18} orthogonal array

Parameters	Levels		
	1	2	3
Cutting speed A (m/min)	33	73	113
Feed rate B (mm/rev)	0.2	0.3	0.4
Depth of cut C (mm)	0.2	0.4	0.6
Combined % reinforcement of SiC-Gr D (%)	5	7.5	10

The work material was machined by different combination of parameters setting with a cutting speeds of 33, 73, 113 m/min, feed rate of 0.2, 0.3, 0.4 mm/rev, depth of cut of 0.2, 0.4, 0.6 mm and combined reinforcement of SiC-Gr with 5, 7.5, 10%.

In this study, the machining features are assessed based on the performance characteristics of surface roughness and material removal rate. The experimental results for L_{18} orthogonal array is shown in Table 2.

3. GREY RELATIONAL ANALYSIS

Grey relational analysis is used to convert the multi objective problem into a single objective problem. In this analysis, data preprocessing is done to normalize the raw data. When the range of series is too large or the optimal value of a quality characteristic is too high, it will influence some factors to be ignored. Therefore the original experimental data are to be normalized to eliminate such effect. The characteristics of original sequence may be “higher the better” or “lower the better” and it can be normalized as follows [9],

If the original sequence is higher the better then, $x_{ij} = \frac{\eta_{ij} - \min_j \eta_{ij}}{\max_j \eta_{ij} - \min_j \eta_{ij}}$ (1)

If the original sequence is lower the better then, $x_{ij} = \frac{\max_j \eta_{ij} - \eta_{ij}}{\max_j \eta_{ij} - \min_j \eta_{ij}}$ (2)

where, η_{ij} and x_{ij} represents original sequence and comparability sequence, $\max_j \eta_{ij}$ and $\min_j \eta_{ij}$ represents the largest and smallest value of original sequence η_{ij}, $i = 1, \dots, m$; m is the number of response variable and $j = 1, \dots, n$; n is the number of experimental runs. The grey relational coefficient is calculated to express the relationship between ideal and normalized data. The grey relational coefficient ξ_{ij} for the i^{th} performance characteristic in the j^{th} experiment can be determined as [10],

$$\xi_{ij} = \frac{\min_i \max_j |x_i^0 - x_{ij}| + \zeta \max_i \max_j |x_i^0 - x_{ij}|}{|x_i^0 - x_{ij}| + \zeta \max_i \max_j |x_i^0 - x_{ij}|} \quad (3)$$

where, x_i^0 is the ideal normalized data for the i^{th} performance characteristic and ζ is identification coefficient, $\zeta = 0.5$ is used normally.

Table 2: Experimental results and grey relational grade values

Ex	Coded value				Surface roughness		Material removal rate		Grade	Order
	A	B	C	D	Ra , µm	S/N (dB)	MRR gm/ min	S/N (dB)		
1	1	1	1	1	4.8	-13.6	2.5	7.9	0.458	17
2	1	2	2	2	6.4	-16.2	20.8	26.4	0.506	15
3	1	3	3	3	8.4	-18.5	26.1	28.3	0.533	14
4	2	1	1	2	3.1	-9.8	12.6	22.0	0.671	8
5	2	2	2	3	5.2	-14.4	23.1	27.3	0.587	10
6	2	3	3	1	6.7	-16.6	31.4	29.9	0.708	4
7	3	1	2	1	2.8	-8.9	16.0	24.1	0.742	2
8	3	2	3	2	4.2	-12.5	28.5	29.1	0.750	1
9	3	3	1	3	4.5	-13.1	19.4	25.8	0.585	11
10	1	1	3	3	4.8	-13.6	9.2	19.3	0.489	16
11	1	2	1	1	5.7	-15.1	4.1	12.3	0.419	18
12	1	3	2	2	5.6	-14.9	23.9	27.6	0.579	12
13	2	1	2	3	3.1	-9.9	14.7	23.4	0.678	6
14	2	2	3	1	5.7	-15.2	29.8	29.5	0.696	5
15	2	3	1	2	4.1	-12.3	24.2	27.7	0.677	7
16	3	1	3	2	3.2	-10.1	19.9	26.0	0.717	3

17	3	2	1	3	4.8	-13.6	16.3	24.3	0.537	13
18	3	3	2	1	5.2	-14.3	25.2	28.1	0.620	9

The overall evaluation of the multi performance characteristics is based on the grey relational grade which is determined by the average sum of grey relational coefficient of response variables in each experiment [10],

$$\gamma_j = \left(1/m\right)\sum_{i=1}^{m}\omega_i\xi_{ij} \quad (4)$$

where γ_j is the grey relational grade for the j^{th} experiment, ω_i the weighing factor for the i^{th} performance characteristic, assume that $\omega_1=\omega_2=1$. Table 2 shows the grey relational grade for each experiment.

4. PARAMETRIC INFLUENCES ON THE PERFORMANCE CHARACTERISTICS

4.1 Individual performance analysis

Analysis of variance (ANOVA) technique is used to obtain the significant effect of each input parameter towards the performance characteristics [11]. The signal to noise ratio (S/N ratio) corresponding to Ra and MRR is determined for each experiment. ANOVA results for S/N ratio values and contribution of each process parameter on the performance characteristics is shown in Table 3.

Table 3: Response table for Ra and MRR

Factor	S/N ratio (dB)			Contribution (%)
	Level 1	Level 2	Level 3	
ANOVA results for surface roughness				
A	-15.352	-13.029	-12.116a	32.00
B	-11.031a	-14.509	-14.957	53.09
C	-12.931a	-13.144	-14.422	7.47
D	-13.970	-12.657	-12.016a	6.14
Error				1.29
Total				100
ANOVA results for material removal rate				
A	20.312	26.644b	26.224	25.38
B	20.467	24.813	27.901b	28.24
C	20.015	26.130	27.035b	29.52
D	21.975	24.731	26.474b	10.42
Error				6.44
Total				100

The feed rate is the most dominant factor on the performance characteristics of surface roughness, with the contribution ratio of 53%. The effect of other parameters on surface roughness is as follows, 32% of cutting speed, 8% of depth of cut and 6% of combined SiC-Gr reinforcement. It is clear from S/N ratio response graph Figure 2, the surface roughness increases with increase in feed rate and depth of cut but decreases with increase in cutting speed and combined % of SiC-Gr reinforcement. Thus the lowest surface roughness values occurred at low values of feed rate and depth of cut with high values cutting speed and combined % of SiC-Gr reinforcement, the results are in agreement with other researchers (Ranganathan et al., 2009; Paulo Davim, 2003). The superior surface finish can be achieved with increase in cutting speeds because at lower cutting speeds build up edge (BUE) formation is observed resulting in low degree of surface finish during continuous turning of composite rods. As the speed increases, the BUE vanishes, chip fracture decreases and hence the roughness decreases. The increase in depth of cut induces high normal pressure and seizure on the rake face of the tool, which promotes the BUE formation finally result in high surface roughness. The increase in volume fraction of SiC-Gr promotes brittleness of the composites and subsequently disappearance of BUE occurs which produces good surface finish. These results are in line with Palanikumar et al., 2007 and Suresh et al., 2013. In 10% of combined SiC-Gr reinforcement, composites offers better surface finish, because the graphite particle forms a glazy layer over the machined surface which reduces the friction.

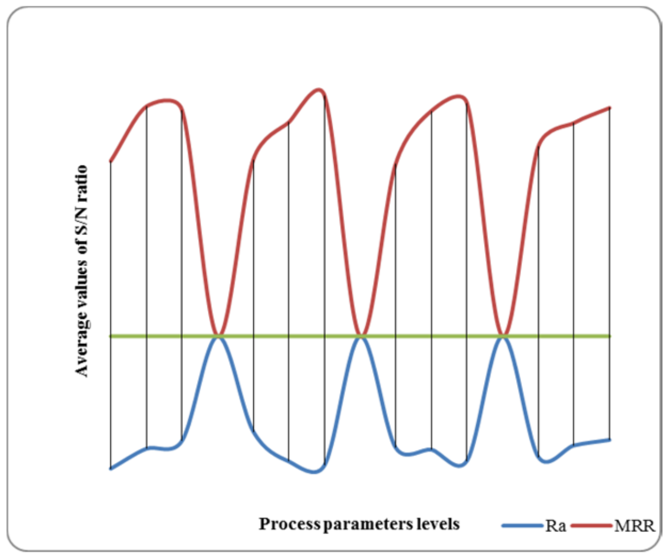

Fig. 2: S/N ratio response graph for Ra and MRR

And for the performance characteristics of material removal rate, the major influencing parameter is depth of cut contributes about 30%, followed by feed rate of 28%, cutting speed of 25% and combined SiC-Gr reinforcement of 10%. From S/N response graph Fig. 2 represents that the material removal rate increases with increase in depth of cut, feed rate and combined % of SiC-Gr reinforcement but at high cutting speed influences gradual decrease in material removal rate. The MRR of the graphite particulate composite is better among the other ceramic particles reinforcement. The increase in combined % of SiC-Gr reinforcement particles reduces the ductility of Al-SiC-Gr hybrid composites [12]. Therefore the machining of Al-SiC-Gr hybrid composites with higher weight fraction of graphite is easy with maximum MRR and less tool wear. The optimum parameters level setting for individual performance characteristics of minimum surface roughness is

$A_3B_1C_1D_3$ and for maximum material removal rate is $A_2B_3C_3D_3$.

4.2 Multiple Performance Analysis

In machining of Al-Si-Gr hybrid composites, multi performances minimum Ra and maximum MRR are the criteria taken for the best performance. In grey relational analysis the original sequence data are first transformed into comparability sequence and subsequently the grey relational coefficient, grey relational grades, orders are determined for all experimental runs. When compared to all grey relational grades in Table 2, the highest grade value is obtained for 8^{th} experimental run. This specifies that the machining parameter level in the experimental run 8 produce the optimum state for the better performance of minimum surface roughness and maximum MRR among all 18 runs. However, the multiple performance characteristics are still refined using Taguchi response table method, so that the optimal combination of parameters level can be determined more accurately. The Taguchi response table based on grey relational grade is determined and the optimum performance of machining Al-SiC-Gr composites is attained at $A_2B_1C_3D_3$ setting. The response table for grey relational grades is listed in Table 4.

Table 4: Response table for grey relational grade

Factor	Grey relational grade			Contribution (%)
	Level 1	Level 2	Level 3	
A	0.4973	0.6695c	0.6585	53.63
B	0.6907c	0.5825	0.6170	21.68
C	0.5578	0.6187	0.6488c	12.40
D	0.6072	0.6282	0.6506c	9.67
Error				2.62
Total				100

c – Optimum state for multi performance characteristics

The cutting speed is the significant parameter which influences the multi performance characteristics with about 54%, followed by feed rate with 22%, depth of cut with 12% and combined SiC-Gr reinforcement with 10%. The graphite particles addition reduces flank wear of the tool. Al-10%(SiC-Gr) has better machinability of minimum surface roughness and maximum MRR for all cutting conditions when compared to other composites.

5. CONFIRMATION EXPERIMENT

The confirmation experiment is the final step to predict and verify the improvement of performance characteristics using the optimal level of machining parameters. After determining the optimum state and predicting the response under this condition, a new experiment is conducted at optimal input parametric setting. The predicted grey relational grade $\alpha_{predicted}$ of the optimal level of parameters can be calculated as:

$$\alpha_{\text{predicted}} = \alpha_x + \sum_{i=1}^{N}(\alpha_i - \alpha_x) \quad (5)$$

where, α_x is total mean of grey relational grade, α_i is the mean of grey relational grade at the optimal level of significant parameters A, B, C and D. N is the number of significant parameters that affect the performance characteristic which is 4. The final confirmation results at optimum setting ($A_2B_1C_3D_3$) for surface roughness and material removal rate are 3.59 μm and 29.28 gm/min respectively. It is found that utilization of the optimal parameter combination enhances the grey relation grade for machining Ai-Si-Gr hybrid composites from 0.750 to 0.827 by 7.7 %.

6. CONCLUSION

The significance of controllable parameters on the performance characteristics of surface roughness and material removal rate are analyzed and the following conclusions are summarized,

The optimum parameters level of machining Al-SiC-Gr hybrid composites for minimum surface roughness within the feasible ranges are cutting speed 113 m/min (level 3), feed rate 0.2 mm/rev (level 1), depth of cut 0.2 mm (level 1) and 10 % of combined SiC-Gr reinforcement (level 3). The combined SiC-Gr reinforcement of 10% yields better surface finish due to decrease in ductility of the base metal.

ANOVA results for material removal rate indicates that depth of cut is the major parameter which influences the material removal rate with about 30%, followed by feed rate with 28%, cutting speed with 25% and combined SiC-Gr reinforcement with 10% of the contribution ratio.

The optimum performance characteristics of higher material removal rate as per Taguchi response table is $A_2B_3C_3D_3$ with cutting speed of 73 m/min, feed rate of 0.4 mm/rev, depth of cut 0.6 mm and 10 % of combined SiC-Gr reinforcement. The increase in graphite addition influences the maximum MRR.

The significant parameters setting in machining of Al-SiC-Gr composites for multi performance characteristics of minimum surface roughness and maximum material removal rate is obtained at 73 m/min of cutting speed (level 2), 0.2 mm/rev of feed rate (level 1), 0.6 mm of depth of cut (level 3) and 10% of combined SiC-Gr reinforcement (level 3).

In machining of Al-SiC-Gr composites, 10% combined SiC-Gr reinforcement confirms the enhancement of performance characteristics of both surface roughness and material removal rate.

The variable parameters are successfully predicted for individual and multi-performance characteristic which in turn reduce the set up time and initial cost of the production.

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