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Effect of high speed turning operation on surface roughness of hybrid metal matrix (Al-SiC_p-fly ash) composite[†]

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Abstract

This paper explains the effect of turning parameters such as cutting speed, feed rate, depth of cut and cutting tool nose radius on surface roughness of hybrid metal matrix (Al-SiC_p-Fly ash) composite. Experiments have been conducted based on the orthogonal array $L_{16}(4)^5$ and surface roughness was tested on the composites turned by an high speed CNC centre lathe. Analysis of variance (ANOVA) was performed to predict the significant parameters and their contribution towards surface finish of the composite. A mathematical model was developed using non-linear regression analysis. Taguchi method and Genetic algorithm have been employed to optimize the turning parameters for optimum surface roughness of the composite. The optimum turning parametric conditions have been checked with the confirmation experiments. It has been noted that the optimum condition of genetic algorithm exhibited better results than the experimental results based on the orthogonal array and the optimum condition of Taguchi method.

Keywords: Hybrid metal matrix composites; High speed turning; Surface roughness; Taguchi method; Genetic algorithm

1. Introduction

Metal matrix composites (MMC) are widely used in many industries such as aerospace, automotive, electronics and medical industries due to their desirable properties like high strength, low weight, high module, low ductility, high wear resistance, high thermal conductivity and low thermal expansion [1-5]. Aluminum, titanium and magnesium alloys are commonly used as metal matrix and silicon carbide (SiC), aluminium oxide (Al_2O_3) and boron carbide (B_4C) are commonly used as reinforcements during the production of MMCs [6-10].

Machinability of MMCs has received considerable attention because of high tool wear associated with machining. MMCs reinforced with SiC_p particles are extremely difficult to machine (Turning, milling, drilling, grinding, etc) due to their extreme abrasiveness [11-13]. Generally, the presence of hard reinforcement particles makes them extremely difficult to machine as they lead to rapid tool wear. Additionally, the production of good surface finish is essential for many components [14, 15]. Studies on machinability of light metal alloy composites reinforced with Al_2O_3/SiC fibers/particles [16, 17] indicate poor machinability due to abrasive wear of tools [18]. Moreover, quality of the machined surface also deteriorates with tool wear [19-21]. Published literature on the machinability of particulate reinforced MMCs indicates that only Polycrystalline diamond tools (PCD) provide a useful tool life when machining these materials with PCD tool, which is harder than Al_2O_3, SiC, B_4C, etc and also does not have a chemical tendency to react with the work piece material [22-25]. However, due to the extremely high cost of PCD tools, less expensive tools like cemented carbides and ceramics are being used to machine these materials.

Now-a-days, aluminum metal matrix composites have emerged as the forerunner for a variety of general and special applications [26-29] due to their superior specific strength, specific stiffness, high temperature capability, lower coefficient of thermal expansion, better wear resistance, improved dimensional stability and amenability to conventional metal forming techniques [30-33]. The present study has been carried out to investigate the effect of high speed turning parameters like cutting speed, feed rate, depth of cut and tool nose radius on the surface roughness of Al-SiC_p-Fly ash metal matrix composites. Taguchi method and genetic algorithm have been employed to find out the optimum parametric conditions for obtaining optimum surface roughness on the turned composites.

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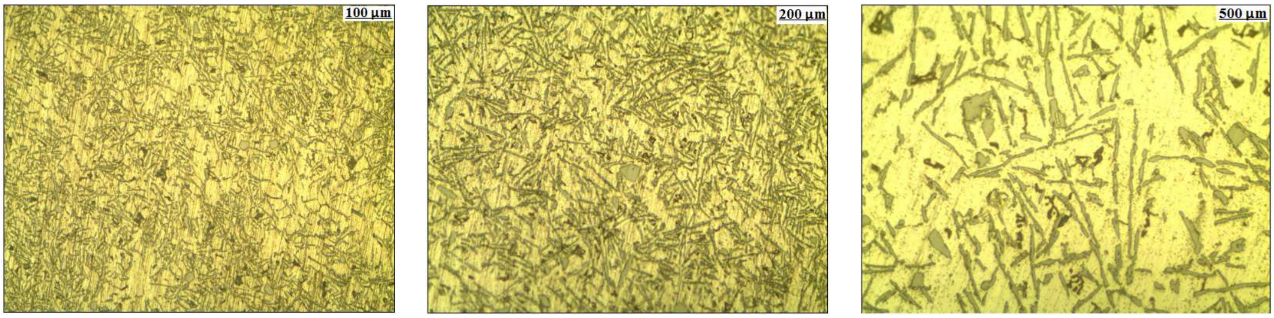

Fig. 1. Microstructures of the hybrid (Al-5%wt SiC_p- 5%wt fly ash) composite.

Table 1. Mechanical properties of hybrid (Al-5%wt SiC_p- 5%wt fly ash) composite.

Density (g/cm^3)	2.7
Yield strength (MPa)	70
Ultimate strength (MPa)	85
Hardness (BHN)	50
Shear strength (MPa)	55

2. Experiment details

2.1 Stir casting of hybrid metal matrix composites

A 450 gm of commercial aluminium (Grade: LM0) was melted in a resistance induction furnace. The melt was degassed by purging hexachloro ethane tablets when the melt temperature reached to 650°C. Simultaneously, 25 gm of silicon carbide (150 µm) and 25 gm of fly ash (100 µm) particles were preheated to 300°C with the aid of muffle furnace. Then the preheated silicon carbide particles were added with the melt and stirred using a mild steel stirrer. The preheated fly ash particles were then added to the melt at the time of formation of vortex due to stirring. The melt temperature was maintained at 650°C-700°C during the addition of the preheated particles. Then the melt was cast into cylindrical shape using a metallic die of SG400 spheroidal graphite iron. The specimens were prepared from the castings for microstructural investigation and mechanical property analysis. The sample microstructures are shown in Fig. 1 and mechanical properties are given in Table 1.

2.2 High speed turning

High speed turning operation was carried out on the cylindrical work piece of hybrid (Al-5%wt SiC_p- 5%wt Fly ash) composite material with help of a CNC lathe shown in Fig. 2. Uncoated tungsten carbide insert was used as cutting tool for turning operation shown in Fig. 3 and no cutting fluid was used during the conduct of experiments. Surface roughness was measured on the turned surface of the work pieces shown in Fig. 4 with the help of profilometer. The turning operation conditions are given in the Table 2.

Fig. 2. High speed CNC turning lathe.

Fig. 3. Turning operation on composite.

Fig. 4. Turned components.

2.3 Design of experiments

Four important control parameters namely cutting speed (A), feed rate (B), depth of cut (C), and nose radius (D), each at four levels were considered in this study and are listed in Table 3. An orthogonal array $L_{16}(4)^5$ was selected for the conduct of experiments. Surface roughness was treated as output response with the category of quality characteristics "smaller the better". The S/N ratio for this response can be estimated by using the Eq. (1).

$$S/N(dB) = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} R_i^2\right) \quad (1)$$

where i = 1,2,…, n (here n = 4) and R_i is the response value for an experimental condition.

Table 2. Operating conditions.

Conditions	Details
Work piece material	Al-5%wt SiC-5%wt fly ash composite
Geometry of work piece	25 mm diameter 100 mm long
Lathe used	CNC Lathe (LMW smart junior)
Insert used	Uncoated carbide insert
Measuring instrument	Profilometer (Surftest), mitutoyo SJ-210
Environment	Dry

Table 3. Parameters and their levels.

Parameter	Notation	Levels			
		1	2	3	4
Cutting speed(rpm)	A	3000	3250	3500	3750
Feed rate(mm/rev)	B	0.05	0.10	0.15	0.20
Depth of cut(mm)	C	0.2	0.3	0.4	0.5
Nose radius(mm)	D	0.2	0.4	0.6	0.8

3. Results and discussion

3.1 Optimum condition by Taguchi method

The S/N ratio was calculated for each experimental condition given in Table 4. Mean value ($\bar{Y}$) of S/N ratios was also calculated using Eq. (2).

$$\text{Mean, } \bar{Y} = \frac{1}{N}\left(\sum_{j=1}^{N} Y_j\right) \quad (2)$$

where j = 1,2,….., N (here N = 16) and Y_j is S/N ratio for j^{th} parametric setting. In order to find optimum level of the turning parameters, average S/N ratio response was estimated for every level of each parameter and the corresponding details are given in Table 5. Based on the highest value of S/N ratio, an optimum level for each parameter (A: 3^{rd} level; B: 4^{th} level; C: 1^{st} level and D: 2^{nd} level) was noted. The optimum turning condition A_3 B_4 C_1 D_2 (cutting speed of 3500 rpm, feed rate of 0.2 mm/rev, depth of cut of 0.2 mm and nose radius of 0.4 mm) was noted. The response graph shown in Fig. 5 described the variation of each process control parameter on the per-

Table 4. Experiments and S/N ratios.

Ex.no	A	B	C	D	Surface roughness (μm)					S/N Ratio Yj (dB)
					R_1	R_2	R_3	R_4	R_a	
1	1	1	1	1	1.92	1.93	1.91	1.94	1.925	-5.68876
2	1	2	2	2	1.84	1.84	1.83	1.85	1.840	-5.29642
3	1	3	3	3	1.88	1.85	1.88	1.89	1.875	-5.4603
4	1	4	4	4	2.11	2.13	2.1	2.12	2.115	-6.50633
5	2	1	2	3	2.55	2.53	2.57	2.58	2.557	-8.15656
6	2	2	1	4	2.05	2.06	2.04	2.05	2.050	-6.23513
7	2	3	4	1	2.12	2.1	2.14	2.12	2.120	-6.52691
8	2	4	3	2	1.85	1.87	1.85	1.88	1.862	-5.40214
9	3	1	3	4	1.85	1.84	1.85	1.86	1.850	-5.3435
10	3	2	4	3	1.75	1.77	1.73	1.76	1.752	-4.87347
11	3	3	1	2	1.65	1.64	1.66	1.65	1.650	-4.34976
12	3	4	2	1	1.55	1.58	1.56	1.52	1.552	-3.82148
13	4	1	4	2	2.47	2.46	2.48	2.42	2.457	-7.81024
14	4	2	3	1	2.45	2.48	2.46	2.42	2.452	-7.79252
15	4	3	2	4	1.85	1.86	1.84	1.83	1.845	-5.32009
16	4	4	1	3	1.75	1.76	1.73	1.74	1.745	-4.83609
Mean ($\bar{Y}$)										-5.8387

Table 5. Average S/N ratio response.

	A	B	C	D
Level1	-5.73795	-6.74977	-5.27743	-5.95742
Level2	-6.58018	-6.04938	-5.64864	-5.71464
Level3	-4.59705	-5.41426	-5.99961	-5.8316
Level4	-6.43973	-5.14151	-6.42924	-5.85126
Max-Min	1.98313	1.60826	1.1518	0.24278
Rank	1	2	3	4
Optimum level	A3	B4	C1	D2

Table 6. ANOVA.

Source	Pool	SS	DOF	MSS	F ratio	PSS	%
A		9.8515	3	3.2838	82.945	9.733	51.13
B		6.1626	3	2.0542	51.886	6.044	31.75
C		2.9031	3	0.9677	24.442	2.784	14.63
D	Yes	0.1187	3	0.0395	1	0	0
Pooled error		0.1187	3	0.0395	1	0.475	2.49
TSS		19.036				19.04	

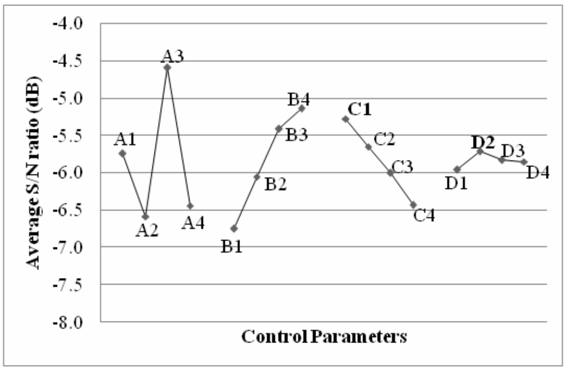

Fig. 5. Response graph.

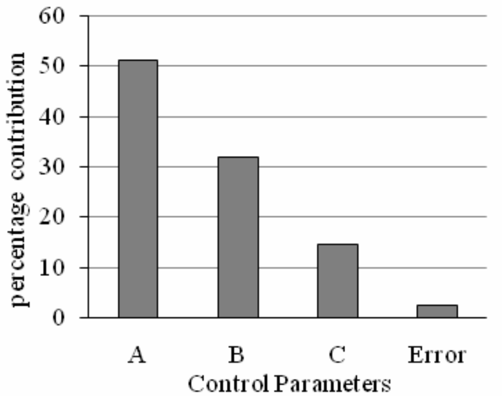

Fig. 6. Percentage contribution.

formance of the turning process.

Analysis of variance was performed on S/N ratios to find the significance of turning parameters and their contribution towards surface roughness. The following terms were calculated and their values are given in the Table 6.

(i) Sum of squares due to mean, $SS_m = N\overline{Y}^2$. (3)

(ii) Sum of squares due to parameter A,

$$SS_A = n_{A1} \times \overline{A_1}^2 + n_{A2} \times \overline{A_2}^2 + n_{A3} \times \overline{A_3}^2 + n_{A4} \times \overline{A_4}^2 - SS_m . \quad (4)$$

Similarly, sum of squares due to parameters B, C and D were calculated. Sum of squares due to parameter D were found to be very less in this study. Therefore, its effect on the output response was assumed to be negligible and treated as an error (pooled error). Sum of squares due to pooled error was also calculated as follows.

$$SS_{pooled\ error} = SS_D . \quad (5)$$

(iii) Total sum of squares,

$$TSS = SS_A + SS_B + SS_C + SS_D . \quad (6)$$

(iv) Degree of freedom for parameter,

$DOF_{parameter}$ = Number of levels of parameter - 1

Degree of freedom for pooled error,

$DOF_{pooled\ error} = DOF_D$.

(v) Mean sum of squares due to parameter A,

$$MSS_A = \frac{SS_A}{DOF_A} . \quad (7)$$

Similarly, mean sum of squares for all other parameters and pooled error were calculated.

(vi) F ratio for parameter A,

$$F_A = \frac{MSS_A}{MSS_{pooled\ error}} . \quad (8)$$

Similarly, F ratio was calculated for parameters B and C. The calculated F ratio for parameters A, B and C was found to be greater than the F distribution table value ($F_{1,3}$= 10.13 at 5% level of significance). Therefore, the parameters A, B and C were confirmed as significant parameters in this study.

(vii) Pure sum of squares due to parameter A,

$$PSS_A = MSS_A - DOF_A \times MSS_{pooled\ error} . \quad (9)$$

(viii) Percentage contribution of parameter A,

$$PC_A = \frac{PSS_A}{TSS} \times 100\ \% . \quad (10)$$

Similarly, pure sum of squares and percentage contribution of parameters B, C and pooled error were calculated. The percentage contribution of pooled error was noted to be less than 5% for output response in this study. The percentage contribution of all significant parameters is clearly shown in Fig. 6.

3.2 Optimum condition by genetic algorithm

By using non-linear regression analysis, the effect of control parameters on average surface roughness (R_a) was modeled as follows.

Table 7. Optimum parametric conditions.

S. No	Optimization tool	Optimum parametric condition			Average surface roughness, R_a (μm)		% error
		Parameters	Coded	Uncoded	Predicted	Tested	
1	Taguchi method	Cutting speed	3	3500 rpm	1.1844	1.135	4.31
		Feed rate	4	0.2 mm/rev			
		Depth of cut	1	0.2 mm			
		Nose radius	2	0.4 mm			
2	Genetic algorithm	Cutting speed	2	3250 rpm	0.3163	0.33	4.15
		Feed rate	4	0.2 mm/rev			
		Depth of cut	1	0.2 mm			
		Nose radius	4	0.8 mm			

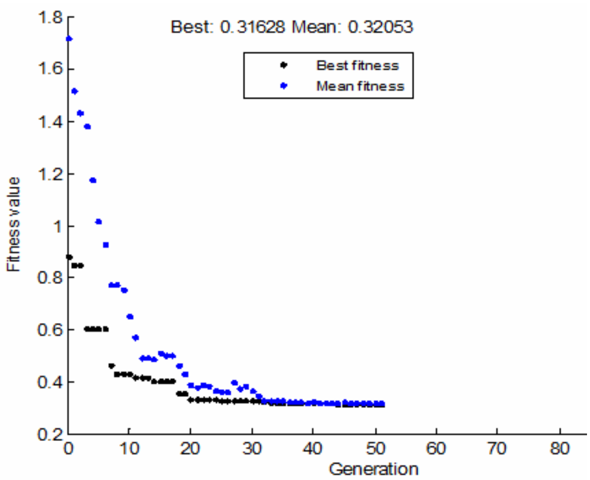

Fig. 7. GA generations.

$$R_a = 2.42881 - 0.45451A - 1.10697B - 0.75564C + 1.70518D + 0.23690A^2 + 0.09085B^2 + 0.08113C^2 - 0.16905D^2 - 0.01758AB - 0.08344AC - 0.09079AD + 0.34994BC - 0.15777BD - 0.11497CD. \quad (11)$$

For this model, it was found that $r^2 = 0.987$ where r is correlation coefficient. The value of r^2 indicates the closeness of the model representing the process. Since r^2 is nearing unity, this model can be taken as an objective function for the application of genetic algorithm through which better parameter settings can be found.

MATLAB genetic algorithm tool was used to find the optimum parametric condition for the minimization of surface roughness in this study. The mathematical model given in Eq. (11) was used as fitness function. The bound for all process parameters (A, B, C and D) were input. Genetic algorithm was run for the evolutionary parameters such as number of iterations (51), population type (double vector), population size (20), cross over probability (0.8), fitness selection function (stochastic) and mutation probability (0.03). It was observed that the fitness value decreased through generations as shown in Fig. 7 and an optimized surface roughness (-0.3163 μm) was obtained in the final generation. The optimum parametric condition in the final generation was noted (cutting speed of 3250 rpm, feed rate of 0.2 mm/rev, depth of cut of 0.2 mm and nose radius of 0.8 mm).

3.3 Confirmation experiments

Confirmation experiments were conducted for the optimum parametric conditions suggested by Taguchi Method and genetic algorithm. Average surface roughness (predicted and tested) values are given in Table 7. It is evident that there is a good agreement between the predicted and actual surface roughness since the error is less than 5%.

The optimum setting for feed rate (0.2 mm/rev) and depth of cut (0.2 mm) was noted to be same in the Taguchi method and Genetic algorithm. From ANOVA, it is evident that the effect of nose radius (0.2 - 0.8 mm) on surface roughness is negligible compared to the other parameters. With respect to cutting speed, the optimum setting of Taguchi method is greater than the setting of genetic algorithm. It is expected that the increase in cutting speed beyond 3250 rpm could result in vibrations during machining, which would cause poor surface finish. From the confirmation experiments, it is proved that genetic algorithm would give better result than Taguchi method in the aspect of surface quality and also indirectly in the aspects of energy savings and production time.

4. Conclusion

The following are the conclusions drawn based on the surface roughness test conducted on hybrid metal matrix (Al-5%wt SiCp - 5% wt Fly ash) composite during high speed turning operation with uncoated carbide insert.

(1) From the results obtained, a regression model has been developed for surface roughness. From the model equation, the value of surface roughness can be predicted if the values of cutting speed, feed and depth of cut are known.

(2) From ANOVA, it can be concluded that cutting speed has a greater influence on the surface roughness followed by

feed rate and depth of cut. Nose radius has least influence on surface roughness.

(3) The validation experiment confirmed that the error occurred was less than 5% between the model and tested value.

(4) The optimal settings of turning process parameters for optimal surface roughness can be used wherever hybrid metal matrix (Al-5%wt SiCp - 5% wt Fly ash) composites require high degree of surface finish.

(5) From the confirmation experiments, it is clear that GA exhibits better result than Taguchi method in the aspects of surface quality and energy savings and production time.

(6) These optimum turning conditions can also be used when the hybrid metal matrix composites are turned for the typical applications like bearings, automobile pistons, cylinder liners, piston rings, connecting rods, sliding electrical contacts, turbo charger impellers, space structures, etc.

Nomenclature

DOF : Degree of freedom
DOE : Design of experiments
MSS : Mean sum of squares
N : Number of experiments
n : Number of observations
PC : Percentage contribution
PSS : Pure sum of squares
R : Readings measured
SS : Sum of squares
TSS : Total sum of squares

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