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Influence of graphite and machining parameters on the surface roughness of Al-fly ash/graphite hybrid composite: a Taguchi approach †

P. Shanmughasundaram[1,*] and R. Subramanian[2]

[1]*Department of Mechanical Engineering, Karpagam College of Engineering, Coimbatore-641032, India*
[2]*Department of Metallurgical Engineering, PSG College of Technology, Coimbatore-641004, India*

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Abstract

This paper presents an experimental investigation on the surface roughness of pure commercial Al, Al-15 wt% fly ash, and Al- 15 wt% fly ash/1.5 wt% graphite (Gr) composites produced by modified two-step stir casting. The effect of reinforcements and machining parameters such as cutting speed, feed rate, and depth of cut on surface roughness, which greatly influence the performance of the machined product, were analyzed during turning operation. The optimum machining parameters were found in minimizing the surface roughness of the materials by using the Taguchi and ANOVA approach. Results show that the presence of the fly ash particles reduces the surface roughness of composites compared with pure Al. The inclusion of 1.5 wt% Gr in the Al-fly ash composite reduces the surface roughness considerably. A scanning electron microscopy investigation was carried out on the machined surfaces of the tested materials. Confirmation tests were performed to validate the regression models.

Keywords: Al-fly ash / graphite composites; ANOVA; Surface roughness; Taguchi; Turning

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1. Introduction

Al matrix composites have emerged as a potentially desirable material because of their excellent engineering properties, particularly in aerospace, automotive, and electronic industries. The surface quality of machined components play a vital role because of the increasing demand for functional attributes such as fitness, fatigue, creep strength, heat transfer, corrosion, and wear behavior. Machining parameters with respect to tool and work piece have to be optimized to attain the minimum cutting forces, increased tooling life, and improved surface texture of machined components. The selection of optimal machining parameters significantly affects the economics of machining operations.

Manna and Bhattacharayya [1] reported that a high cutting speed with low feed rate and low depth of cut enhances the quality of surface roughness during the turning of Al reinforced with 10% SiC_p composites. Seeman et al. [2] studied tool wear and surface roughness evaluation through the response surface methodology in machining Al reinforced with a 20% SiCp composite. The surface roughness is low at high speeds, low feed rates, and low depths of cut ranges. Hoecheng et al. [3] investigated the influence of speed, feed, depth of cut, tool rake angle, and cutting fluid on the surface roughness of Al alloy-graphite (Gr) composites. Yuan and Dong [4] analyzed the effect of reinforcement, cutting angle, feed rate, and speed on the surface finish in the ultra-precision diamond turning of Al-SiC composites. Paulo Davim [5] employed the Taguchi method for optimizing the cutting conditions to obtain a good surface finish. Results show that the cutting velocity and feed have considerable influences on roughness, followed by depth of cut. Ciftci et al. [6] analyzed the influence of different particle sizes of SiC and cutting speed on tool wear and surface roughness during the machining of Al/SiC composites by employing a cubic boron nitride cutting tool. Tool wear was mainly observed on the flank side with a strong influence by abrasive reinforcement.

Suresh et al. [7] developed a binary coded genetic algorithm-based model to find the optimum surface roughness. Muthukrishnan and Paulo Davim [8] used ANOVA and ANN modeling techniques to predict the surface roughness. They found that the feed rate has the highest physical influence on surface roughness, followed by depth of cut and cutting speed, in the machining of Al/SiC composites. Al-Ahmari [9] developed empirical models for tool life, surface roughness, and cutting force for turning operations. The reinforcement particles used in the manufacturing of metal matrix composites (MMCs) are harder than most cutting tool materials, thus resulting in high tool wear because of abrasive action. Most

*Corresponding author. Tel.: +91 9842461672, Fax.: +91 422 2619046
E-mail address: sunramlec@rediffmail.com
† Recommended by Associate Editor Song Min Yoo

researchers have reported that diamond is the most preferred tool material for machining MMCs. Tomac et al. [10] suggested that cemented carbide and polycrystalline diamond (PCD) tools are preferred for rough and finish machining, respectively.

Hwang and Lee [11] investigated the wet turning process of AISI 1045 work material to analyze the effect of cutting parameters on machinability. Sahin and Sur [12] reported that coated carbide tools have higher wear resistance, lower heat generation, and lower cutting forces compared with carbide tools during machining. The flank wear of coated carbide tools under all cutting conditions was less than that of carbide tools.

The main concern in MMC machining is the extremely high tool wear caused by the abrasive action of the ceramic reinforcement particles. Tool wear directly affects the surface roughness and dimensional deviation of machined components. Studies on the machinability of Al-fly ash composites are important because of the presence of fly ash particles, which increases the hardness, tensile strength, and wear resistance of the Al matrix [13].

Although PCD tools show better tool life and surface finish, the high cost of PCD tools increases the machining cost of MMCs. Kok [14] reported that the average surface roughness of Al 2024 reinforced with Al_2O_3 composites is considerably less than that of the Al alloy when machined by using the TiN (K10) coated cutting tool. The machinability analysis of MMCs is clearly an important area of research in finding the optimum machining parameters that increase productivity and minimize tooling cost without compromising the surface finish. TiAlN/AlCrN multi-layered PVD-coated carbide tools can be employed in MMC machining because of their high hardness, chemical stability, and high resistance to wear and oxidation. According to metal cutting theory, the feed rate and tool-nose radius decide the pitch and amplitude of the surface profile of the machined component. Basheer et al. [15] studied the influence of the size of the reinforcement and the machining parameters on the surface roughness of the SiC-reinforced Al composites. They reported that the best surface quality is obtained with low feed rate, small particle size, and large tool-nose radius. Given that limited studies have been conducted on surface roughness during the hybrid MMC machining, an attempt has been made to minimize the surface roughness by optimizing the three machining parameters, namely, cutting speed, feed rate, and depth of cut, by the Taguchi and ANOVA techniques in turning of Al, Al-15 wt% fly ash, and Al-15 wt% fly ash/1.5 wt% Gr composites. In this study, a TiAlN/AlCrN multi-coated carbide tool with a 0.8 mm nose radius was chosen to optimize the objective function subject to machining constraints.

2. Experimentation

2.1 Preparation of the composite material

In this study, 99.5% pure Al ingot was used as the matrix material and fly ash particles at 50 µm to 100 µm were used as reinforcements. The fly ash particles consisted of SiO_2 (54.27%), Al_2O_3 (34.73%), Fe_2O_3 (6.1%), CaO (2.4%), and MgO (2.1%). For hybrid composites, 1.5 wt% Gr particles with an average size of 50 µm were used as additional reinforcement material. Approximately 1.5 wt% Mg was added to the melt to promote the wetting action between the Al matrix and reinforcement particles.

Al-fly ash composites were produced by modified two-step stir casting. Al was charged into the Gr crucible, and the furnace temperature was raised to a liquidus temperature of 670 °C to melt the Al scraps completely and then stirred at 300 rpm. During stirring, Mg and preheated fly ash/Gr particles were added into the molten Al at the side of the vortex. Stirring was performed for 5 min. The melt temperature was lowered to 620°C to obtain a semi-solid state and stirred for 5 min in the semi-solid state. The composite slurry was again reheated to a liquidus temperature of 655°C and stirred at 300 rpm for 5 min. The rotary and reciprocating movements of the impeller during stirring prevented the settling of reinforcement particles at the bottom of the crucible and maintained the particles in a state of suspension, thereby enhancing the uniform distribution of the particles. Finally, the composite slurry was poured into the steel mold to solidify. Degassing was done by purging hexachloroethane tablets, and argon gas was blown at a rate of 2 CC/min into the crucible during the process to minimize the high temperature oxidation associated with Al and Mg.


Fig. 1. CNC lathe.

2.2 Machinability test

The experiment was conducted by using a computer numerical controlled (CNC) lathe (Fig. 1). A TiAlN/AlCrN multi-layered coated carbide tool insert (CNMG120408NSU/AC510U) was clamped mechanically in a rigid PCLNL-2020 K12-type tool holder. The split die and several specimens are shown in Fig. 2. The size of the work piece is 24 mm (diameter) × 85 mm (length). The mean surface roughness (Ra) was measured in the direction of the tool movement of the machined surface by using a transverse tracing drive unit-type surface roughness tester, i.e., Mitutoyo SJ-210 (Fig. 3). A summary of the experimental conditions is provided in Table 1.

Table 1. Summary of experimental conditions.

Work piece	Bar size: Φ24 mm × length 85 mm Machining length = 60 mm
Tool holder	PCLNL-2020 K12 Square shape (length 125 mm, 20 mm width, 20 mm thick)
Tool insert	CNMG120408NSU/SUMITOMO (AC510U) Rake angle = 13°; tool radius = 0.8 mm, diamond 80°
Spindle speed (rpm)	3000, 3750, 4500
Cutting speed (m/min)	226.08, 282.60, 339.12
Feed rate (mm/rev)	0.05, 0.1, 0.15
Depth of cut(mm)	0.1, 0.2, 0.3
Tool overhang (mm)	20 to 25
Work piece overhang (mm)	60
Cutting condition	Dry
Surface roughness measuring device	Transverse tracing drive unit-type SJ-210 Mitutoyo Measuring range - 360 µm (−200 µm to +160 µm) Resolution = 25 µm/0.002 µm Measuring force: 4 mN

Fig. 2. Split die and specimens.

Fig. 3. Surface roughness of the measuring device.

3. Results and discussion

3.1 Design of experiments

Taguchi's parameter design provides a systematic and efficient methodology for determining the optimum parameters that affect process and performance. The design eliminates the need for repeated experiments, thus saving time, material, and cost. In the Taguchi method, "signal" expresses the desirable value (mean), and "noise" expresses the undesirable value (standard deviation) for the output quality characteristics. S/N (signal-to-noise) ratios are calculated from the quadratic loss function and expressed in a decibel scale. The "smaller is better" S/N ratio is chosen to predict the optimum parameters because a lower surface roughness of the specimens is preferred. The experiments were conducted according to the L27 orthogonal array. Accordingly, 27 experiments were conducted, and each experiment was repeated twice to minimize experimental errors. The design of the experiment software MINITAB 15 was used to analyze the experimental data. The machining parameters and corresponding levels used are presented in Table 2. The measured surface roughness values and S/N ratios are provided in Table 3.

Table 2. Machining parameters and levels.

Level	Cutting speed (m/min) (A)	Feed rate (mm/rev) (B)	Depth of cut (mm) (C)
I	226.08	0.05	0.1
II	282.60	0.1	0.2
III	339.12	0.15	0.3

3.2 S/N ratio results

The S/N ratio is obtained through the Taguchi technique. The S/N ratio for each parameter was determined by averaging the S/N ratios at the corresponding level. The influence of parameters such as cutting speed, feed rate, and depth of cut on the surface roughness was analyzed. The ranking of the parameters is presented in S/N response in Tables 4-6. Given that the process parameters with the highest S/N ratio will yield the optimum quality with minimum variance, we can determine from the response tables that the feed rate is a dominant parameter on the surface roughness of tested specimens, followed by cutting speed and depth of cut.

The average S/N ratios were plotted for each parameter against each of its levels (Figs. 4(a)-4(c)). The optimum parameters are cutting speed (339.12 m/min), feed rate (0.05 mm/rev), and depth of cut (0.1 mm) irrespective of the machined surface of the tested materials.

3.3 ANOVA results

ANOVA determines the optimum combination of machining parameters, namely, cutting speed, feed rate, and depth of cut, in minimizing the surface roughness of the machined specimens by investigating the relative importance among the machining parameters. ANOVA is conducted at 5% significance level to study the contribution of the parameters. A *P*-value for each independent parameter in the model is shown in

Table 3. Measured values and S/N ratios for surface roughness of Al, Al-fly ash, and Al-fly ash/Gr composites.

Exp. No	Parameters			Measured values (Surface roughness, μm)			S/N ratio		
	Cutting speed (m/min) (A)	Feed rate (mm/rev) (B)	Depth of cut (mm) (C)	Al	Al−FA	Al−FA /Gr	Al	Al−FA	Al−FA /Gr
1	226.08	0.05	0.1	2.112	1.190	1.140	−6.4939	−1.5109	−1.1381
2	226.08	0.05	0.2	2.099	1.221	1.201	−6.4402	−1.7343	−1.5909
3	226.08	0.05	0.3	2.200	1.409	1.341	−6.8485	−2.9782	−2.5486
4	226.08	0.1	0.1	2.401	1.590	1.399	−7.6078	−4.0279	−2.9164
5	226.08	0.1	0.2	2.537	1.660	1.508	−8.0864	−4.4022	−3.5680
6	226.08	0.1	0.3	2.880	1.886	1.850	−9.1878	−5.5108	−5.3434
7	226.08	0.15	0.1	2.913	2.103	2.012	−9.2868	−6.4568	−6.0726
8	226.08	0.15	0.2	3.141	2.132	2.103	−9.9414	−6.5757	−6.4568
9	226.08	0.15	0.3	3.200	2.253	2.209	−10.103	−7.0552	−6.8839
10	282.60	0.05	0.1	1.800	0.992	0.917	−5.1055	0.0698	0.7526
11	282.60	0.05	0.2	1.912	1.061	1.096	−5.6298	−0.5143	−0.7962
12	282.60	0.05	0.3	1.956	1.103	1.211	−5.8274	−0.8515	−1.6629
13	282.60	0.1	0.1	2.100	1.199	1.290	−6.4444	−1.5764	−2.2118
14	282.60	0.1	0.2	2.291	1.235	1.218	−7.2005	−1.8333	−1.7129
15	282.60	0.1	0.3	2.324	1.389	1.335	−7.3247	−2.8540	−2.5096
16	282.60	0.15	0.1	2.388	1.602	1.562	−7.5607	−4.0933	−3.8736
17	282.60	0.15	0.2	2.412	1.723	1.710	−7.6475	−4.7257	−4.6599
18	282.60	0.15	0.3	2.440	1.928	1.881	−7.7478	−5.7021	−5.4878
19	339.12	0.05	0.1	1.674	0.755	0.680	−4.4751	2.4411	3.3498
20	339.12	0.05	0.2	1.699	0.812	0.722	−4.6039	1.8089	2.8293
21	339.12	0.05	0.3	1.912	0.935	0.813	−5.6298	0.5838	1.7982
22	339.12	0.1	0.1	1.871	0.998	0.845	−5.4415	0.0174	1.4629
23	339.12	0.1	0.2	1.988	1.013	0.984	−5.9683	−0.1122	0.1401
24	339.12	0.1	0.3	2.102	1.251	1.099	−6.4527	−1.9451	−0.8200
25	339.12	0.15	0.1	2.243	1.299	1.155	−7.0166	−2.2722	−1.2516
26	339.12	0.15	0.2	2.390	1.353	1.229	−7.5680	−2.6260	−1.7910
27	339.12	0.15	0.3	2.435	1.437	1.355	−7.7300	−3.1491	−2.6388

Table 4. Response table for S/N ratios (surface roughness of pure Al).

Level	A: cutting speed (m/min)	B: feed rate (mm/rev)	C: depth of cut (mm)
1	−8.222	−5.673	−6.604
2	−6.721	−7.079	−7.010
3	−6.098	−8.289	−7.428
Delta	2.123	2.616	0.824
Rank	2	1	3

Table 5. Response table for signal-to-noise ratios (surface roughness of Al-fly ash composite).

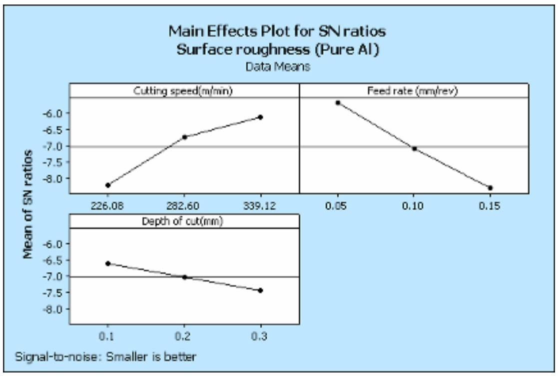
Level	A: cutting speed (m/min)	B: feed rate (mm/rev)	C: depth of cut (mm)
1	−4.4725	−0.2984	−1.9344
2	−2.4534	−2.4716	−2.3016
3	−0.5837	−4.7396	−3.2736
Delta	3.8887	4.4411	1.3392
Rank	2	1	3

the ANOVA table (Table 7). When the *P*-value is less than 0.05, the parameter can be considered statistically highly significant.

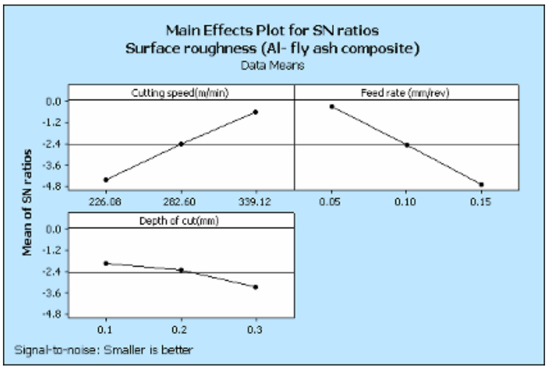
The ANOVA results show that the machining parameters, namely, cutting speed, feed rate, and depth of cut, have a value of less than 0.05. This result shows that these machining parameters are highly significant at a 95% confidence level irrespective of the tested materials. The interaction effect of the cutting speed with a feed rate of (A*B) is a significant model term that influences the surface roughness of the tested materials because this term has a *P*-value < 0.05. Given that

Table 6. Response table for signal-to-noise ratios (surface roughness of Al-fly ash/Gr composite).

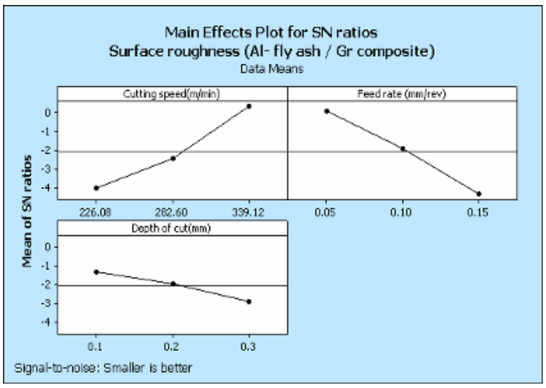
Level	A: cutting speed (m/min)	B: feed rate (mm/rev)	C: depth of cut (mm)
1	−4.0576	0.1104	−1.3221
2	−2.4625	−1.9421	−1.9563
3	0.3421	−4.3462	−2.8996
Delta	4.3997	4.4566	1.5776
Rank	2	1	3



(a) Pure Al



(b) Al-fly ash composite



(c) Al-fly ash/Gr composite

Fig. 4. Main effects plot for SN ratios and surface roughness of (a) pure Al; (b) Al-fly ash composite; (c) Al-fly ash/Gr composite.

Table 7. ANOVA analysis for surface roughness.

Factor	Dof	SS	F-value	*P*-value	Pc%
Pure Al					
A: cutting speed	2	1.60488	156.79	0.000	38.05
B: feed rate	2	2.13425	208.51	0.000	50.60
C: depth of cut	2	0.21060	20.58	0.001	4.99
A × B	4	0.18008	8.80	0.005	4.27
A × C	4	0.01928	0.94	0.487	0.45
B × C	4	0.02762	1.35	0.332	0.65
Error	8	0.04094			0.97
Total	26	4.21765			100
Al-fly ash composite					
A: cutting speed	2	1.74948	372.08	0.000	40.14
B: feed rate	2	2.25544	479.69	0.000	51.75
C: depth of cut	2	0.20779	44.19	0.000	4.76
A × B	4	0.11626	12.36	0.002	2.66
A × C	4	0.00225	0.24	0.909	0.05
B × C	4	0.00763	0.81	0.552	0.17
Error	8	0.01881			0.43
Total	26	4.35764			100
Al-fly ash/Gr composite					
A: cutting speed	2	1.93316	146.04	0.000	43.35
B: feed rate	2	2.09422	158.20	0.000	46.96
C: depth of cut	2	0.24924	18.83	0.001	5.58
A × B	4	0.11692	4.42	0.035	2.62
A × C	4	0.00796	0.30	0.870	0.18
B × C	4	0.00516	0.19	0.934	0.11
Error	8	0.05295			1.18
Total	26	4.45961			100

DoF: degrees of freedom; Seq.SS: sequential sums of squares; Adj.MS: Adjusted sums of squares; Pc: percentage of contribution.

the *P*-value for the interaction terms (B*C) and (A*C) are greater than 0.05, the model terms may be considered statistically insignificant.

The last column of the table shows the percentage contribution (Pc %) of each variable in the total variation and indicates the degree of influence of each variable on the surface roughness. The feed rate (46.96%) is the major factor that influences the surface roughness of the Al-fly ash/Gr composite, followed by the cutting speed (43.35%) and depth of cut (5.58%). A similar trend was observed for pure Al and Al-fly ash composites.

The error term has little or no influence on surface roughness. From the outcome of the S/N ratio and ANOVA, we infer that the results closely match each other.

3.4 Multiple linear regression models

Multiple linear regression equations were developed to establish the correlation among the parameters on the response. The value of regression coefficient R^2 (0.9903) is in good agreement with the adjusted R^2 (0.9685) for the surface roughness of the pure Al. R^2 (0.9957) is in good agreement with the adjusted R^2 (0.9860) for the surface roughness of the Al-fly ash composite. The value of the regression coefficient R^2 (0.9881) is in good agreement with the adjusted R^2 (0.9614) for surface roughness of the Al-fly ash/Gr composites. Considering that both values are reasonably close to unity, the models provide a good explanation for the relationship between the independent parameters and responses.

The regression equation developed for the surface roughness of the pure Al is as follows:

2.81 − 0.00508 cutting speed + 6.89 feed rate + 1.08 depth of cut. (1)

The regression equation developed for the surface roughness of the Al-fly ash composite is as follows:

2.03 − 0.00550 cutting speed + 7.06 feed rate + 1.03 depth of cut. (2)

The regression equation developed for the surface roughness of the Al-fly ash/Gr composite is as follows:

2.05 − 0.00578 cutting speed + 6.77 feed rate + 1.16 depth of cut. (3)

We can observe from Eqs. (1)-(3) that the feed rate % (B) plays a major role on surface roughness, followed by cutting speed (A) and depth of cut (C). The coefficient associated with cutting speed (A) is negative, thus indicating that the surface roughness of the machined surfaces decreases with increasing cutting speed. Conversely, the surface roughness increases with increasing feed rate and depth of cut because the coefficients associated with these factors are positive.

Feed rate has a larger effect on surface roughness compared with the depth of cut according to its coefficient value in the machining of tested materials.

3.5 Confirmation test

The confirmation test is the final step in the design of the experiment process. Confirmation tests were conducted to validate the statistical analysis by selecting experimental conditions that are different from those employed in the analysis.

The parameters used in the confirmation test are presented in Table 8. The results of the confirmation tests are presented in Table 9.

Experimental results were compared with the computed values developed from the regression models. Table 9 shows that the experimental values and calculated values from the regression equation are nearly the same with the least error (±5%). The resulting equations are capable of predicting the surface roughness to an acceptable level of accuracy.

Table 8. Parameters used in the confirmation test.

Test	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)
I	263.75	0.15	0.15
II	301.44	0.10	0.2

Table 9. Results of confirmation test.

Material	Test I			Test II		
	Surface roughness (Ra)			Surface roughness (Ra)		
	Model equation	Expt.	Error (%)	Model equation	Expt.	Error (%)
Al	2.665	2.745	-2.978	2.183	2.268	-3.85
Al –fly ash composite	1.792	1.725	3.782	1.284	1.220	4.99
Al –fly ash/ Gr composite	1.714	1.789	-4.316	1.216	1.270	-4.36

3.6 Discussion

From the main effects plots of the S/N ratios (Figs. 4(a)-4(c)), 339.12 m/min was found to be the optimal cutting speed to obtain the minimum surface roughness for all tested materials. A higher cutting speed results in a significant improvement in the surface finish. The size of the built-up edge (BUE) is reduced because of decreasing chip tool contact length, thus explaining the quality of the surface finish. The optimum feed rate was found to be 0.05 mm/rev. The lowest depth of cut (0.1 mm) appears to be the optimal value in attaining a low value of surface roughness. The feed rate is a dominant parameter on the surface roughness, followed by cutting speed and depth of cut, irrespective of the materials machined. However, the ANOVA table (Table 7) shows that the depth of cut has the lowest contribution on the surface roughness of the tested specimens.

3.6.1 Influence of machining parameters on surface roughness

Surface roughness values were plotted with different cutting speeds (Fig. 5(a)), thus keeping the other two parameters, that is, feed rate (0.05 mm/rev) and depth of cut (0.1 mm), as constants at their optimum values to analyze the effect of cutting speed on surface roughness.

Fig. 5(a) illustrates that an increase in cutting speed decreases the surface roughness of the machined surfaces of all tested materials. Surface roughness decreases from 1.14 μm to 0.680 μm when cutting speed increases from 226.08 m/min to 339.12 m/min at a constant feed rate (0.05 mm/rev) and depth of cut (0.1 mm) during the machining of the Al-fly ash/Gr composite. The considerable reduction (40%) in surface roughness is achieved by increasing the cutting speed by 50%. Similarly, the surface roughness of the Al-fly ash composite and pure Al decreases by 36% and 21%, respectively. Higher cutting speeds enhance material removal within a short time, thus resulting in a reduction of BUE size and substantial improvements in the surface finish of tested materials. Composite materials also show a better surface roughness than non-reinforced pure Al at all cutting speeds. The enhanced brittle nature of the composite surface and the subsequent vanishing of the BUE during machining can explain this finding.

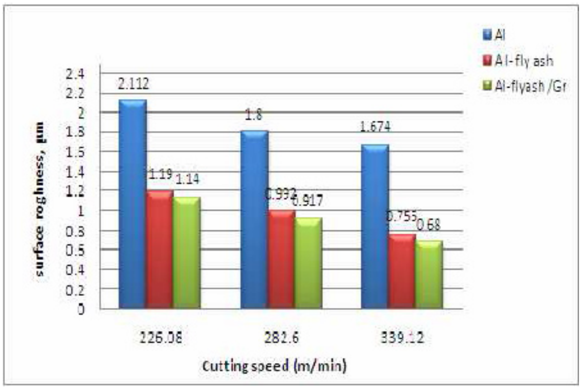
Similar observations were made by Suresh Kumar Reddy et al. [16] during the machining of Al alloy-SiC composites. They reported that the presence of reinforcement enhances machinability in terms of surface roughness and lowers the tendency to clog the cutting tool when compared to a non-reinforced Al alloy.

Fig. 5(a) also demonstrates that the surface roughness of the Al-fly ash/Gr composite decreases by approximately 10% compared with the Al-fly ash composite machined at a cutting speed of 339.12 m/min, feed rate of 0.05 mm/rev, and depth of cut of 0.5 mm. The incorporation of 1.5 wt% Gr particles as a supplementary reinforcement reduces the surface roughness considerably. The increased burnishing (or) honing effect of Gr particles act as a lubricant and reduce the coefficient of friction between the tool cutting edge and work piece. Given that Gr particles are dense and soft, they are easily spread on the work piece surface. The Gr particles tend to prevent the direct contact of the cutting edge of the tool and reduce the ploughing effect during machining.

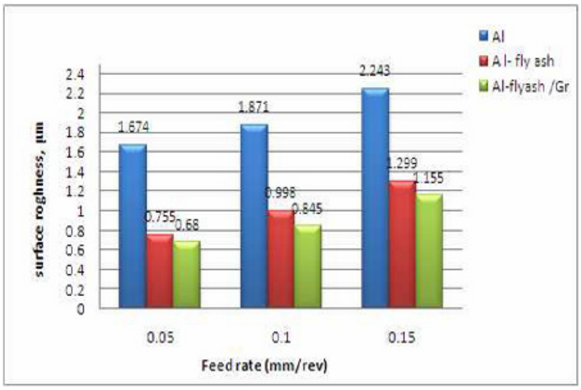
To analyze the effect of the feed rate on surface roughness, surface roughness values at different feed rates were plotted while keeping the optimum cutting speed at 339.12 m/min and depth of cut at 0.1 mm.

Fig. 5(b) illustrates that the surface roughness of all tested materials apparently follows an increasing trend with increasing feed rate. The results show that the surface roughness of pure Al and Al-fly ash composite increases by 34% and 72%, respectively, when the feed rate increases from 0.05 mm/rev to 0.15 mm/rev at optimum cutting speed (339.12 m/min) and depth of cut (0.1mm) values. A higher feed rate induces higher friction at the interface between the tool and pure Al, thus generating heat. This heat tends to soften the Al, which then adheres onto the tool face to form the BUE and increases the surface roughness of the machined Al surface.

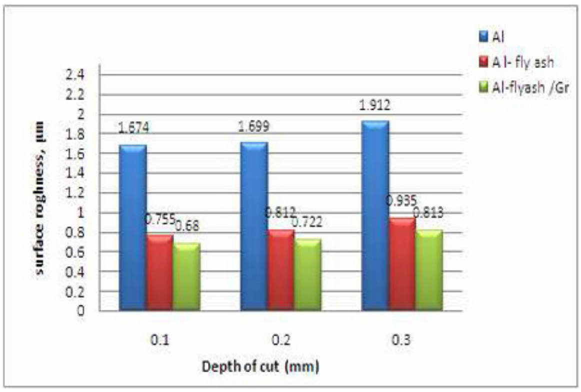
The surface finish of Al-fly ash composites deteriorate more rapidly than that of Al because a higher feed rate causes higher interfacial temperature and decreases the bonding effect between fly ash particles and the Al matrix. Some of the fly ash particles are partially or completely removed from the machined surface during machining, thus increasing surface roughness. Fine chips that break off also have a tendency to attach onto the cutting tool and weld themselves to the edge of the tool because of high temperatures, thus leading to the formation of BUE and increasing the roughness. The surface roughness of the Al-fly ash/Gr composite increases by 69%



(a)



(b)



(c)

Fig. 5. (a) Effect of cutting speed on surface roughness; (b) Effect of feed rate on surface roughness; (c) Effect of depth of cut on surface roughness.

when the feed rate increases from 0.05 mm/rev to 0.15 mm/rev. This small reduction in surface roughness is achieved compared with the Al-fly ash composite because of the incorporation of Gr particles.

Fig. 5(b) shows that the surface roughness of the Al-fly ash composite decreases by approximately 55% compared with that of pure Al when machined under optimum cutting parameters. The addition of reinforcement particles can be inferred to reduce the surface roughness of composites con-

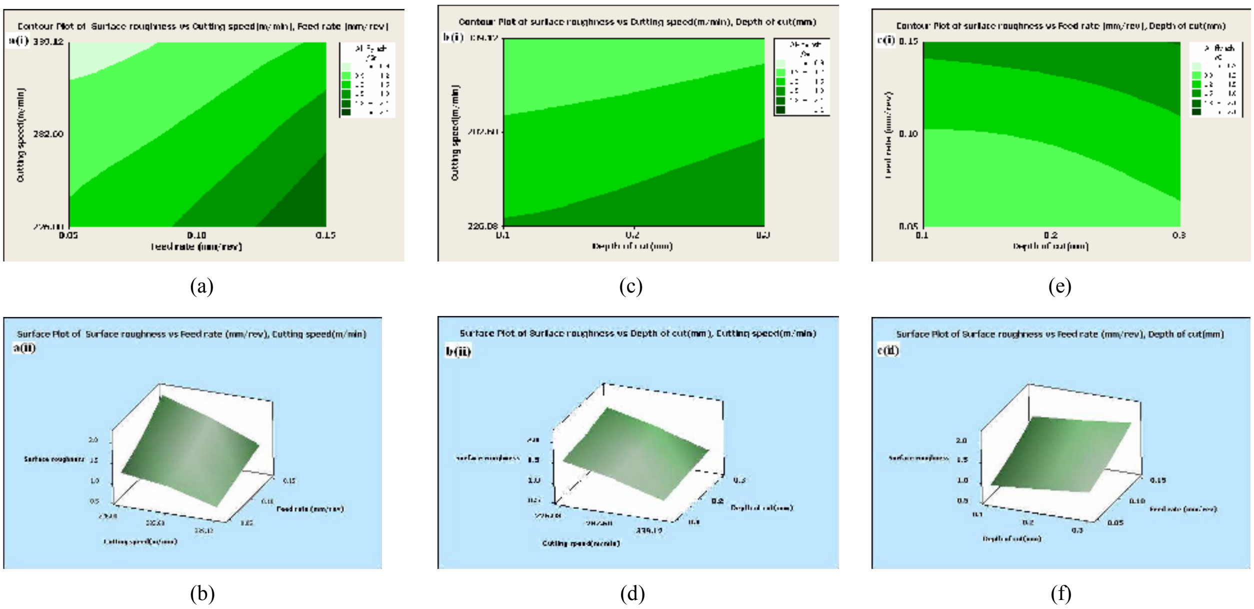


Fig. 6. (a) Contour plot for surface roughness versus feed rate and cutting speed; (b) Surface plot for surface roughness versus feed rate and cutting speed; (c) Contour plot for surface roughness versus cutting speed and depth of cut; (d) Surface plot for surface roughness versus cutting speed and depth of cut; (e) Contour plot for surface roughness versus feed rate and depth of cut; (f) Surface plot for surface roughness versus feed rate and depth of cut.

siderably. Palanikumar and Karthikeyan [17] reported that a lower feed rate and higher volume fraction of SiC decreases the surface roughness of composites. They emphasized that the higher feed rate results in the formation of BUE, thus increasing the roughness of composites. Their findings are consistent with those of our work.

The average surface roughness value with respect to the different depths of cut at an optimum cutting speed of 339.12 m/min and feed rate of 0.05 mm/rev is shown in Fig. 5.3 to analyze the effect of the depth of cut on the surface roughness of the tested materials.

Fig. 5(c) indicates that the surface roughness of the tested materials increases with increasing depth of cut. The minimum surface roughness is achieved when the depth of cut is maintained at 0.1 mm irrespective of the materials machined. The surface roughness of the Al-fly ash/Gr composite increases by 20% when the depth of cut increases from 0.1 mm to 0.3 mm under optimum cutting speed and feed rate conditions. The surface roughness of pure Al and Al-fly ash composite increase by approximately 14% and 24%, respectively.

At a constant cutting speed and feed rate, an increase in the depth of cut increases the chip cross-sectional area, thus causing more cutting force and increasing the surface roughness of the machined surfaces. A greater depth of cut results in high normal pressure and seizure on the cutting edge of the tool. Moreover, a greater depth of cut promotes BUE formation because of increased area of contact. In the case of Al-fly ash composites, an increase in the depth of cut increases subsurface damage, which deteriorates the surface finish. However, the depth of cut has no significant influence on the roughness until it the depth of cut is large enough to cause chatter.

Figs. 5(a)-(c) show that the incorporation of 1.5 wt% Gr in the Al-fly ash composite reduces the surface roughness unlike in both Al and Al-fly ash composites, irrespective of the feed rate, cutting speed, or depth of cut. Adel Mohammed Hassan et al. [18] reported that the addition of Gr particles of more than 1 wt% results in the deterioration of the hardness and strength of the composites. Given that the incorporation of Gr adversely affects the mechanical properties of the Al matrix, a compromise is crucial in choosing the amount of Gr as a supplementary reinforcement to improve the machinability of the composites without sacrificing the mechanical properties. However, the addition of a higher weight percentage of Gr leads to the formation of small craters and tiny valleys on the machined surface of the composite because of the removal of soft Gr particles during machining, thus increasing the surface roughness value.

3.6.2 Construction of surface roughness maps

The contour and response surface plots, which are the graphical representation of the regression equations, can be used to establish and visualize the relationship between the response and experimental levels of each parameter. In a contour plot, the values for two parameters are represented on the *x*- and *y*-axes, whereas the values for a third parameter are represented by shaded regions. A contour surface provides a 2D view, whereas a surface plot provides a 3D view.

Variations in the surface roughness of Al-fly ash/Gr composites under different cutting speeds, feed rates, and depths of cut conditions are plotted (contour and surface plots) in Figs. 6(a)-(f).

Figs. 6(a) and (b) show that surface roughness increases at higher feed rates and low cutting speed conditions, whereas surface roughness decreases at low feed rates and higher cutting speed conditions. Low surface roughness was obtained at a feed rate of 0.05 mm/rev and a cutting speed of 339.12 m/min. A significant interaction between the feed rate and cutting speed affecting the surface roughness can be concluded. The ANOVA analysis also shows that because the *P*-value for the interaction effect between the cutting speed and the feed rate is less than 0.05, the interaction term significantly influences the surface roughness. The surface roughness of the machined surface can be enhanced with a reduction in the feed rate, specifically at higher cutting speeds. Therefore, a good combination of cutting speed and feed rate has to be selected to improve the surface roughness.

Both the contour plot (Fig. 6(c)) and surface plot (Fig. 6(d)) demonstrate that the surface roughness gradually increases with decreasing cutting speed and increasing depth of cut. The minimum surface roughness occurs at a cutting speed of 339.12 m/min and depth of cut of 0.1 mm.

The contour plot (Fig. 6(e)) and surface plot (Fig. 6(f)) illustrate that the decreasing trend of surface roughness is in accordance with the gradual decrease in feed rate and depth of cut. The minimum surface roughness occurs at a feed rate of 0.05 mm/rev and depth of cut of 0.1 mm. Contour and surface plots indicate that the surface roughness decreases with increasing cutting speed and decreasing feed rate and depth of cut. The earlier discussion on the effect of machining parameters on surface roughness is supported by these results.

3.7 SEM analysis of machined samples

Machined surface morphology of pure Al and Al-fly ash/Gr composites were examined by the optimum process parameters by employing scanning electron microscope to reveal the surface texture.

The SEM image of the pure Al after machining is shown in Fig. 7(a). The SEM images of the Al-fly ash/Gr composite before and after machining are shown in Figs. 7(b) and 7(c), respectively.

The SEM image of the machined surface of the Al-fly ash/Gr composite reveals that a relatively better surface finish is achieved compared with that of pure Al, which has large feed marks. Given that the chips are broken by dispersed reinforcement particles during the machining of Al-fly ash/Gr composite at optimum conditions, the entrapment of chips between the work piece and tool is avoided. Therefore, BUE formation on the tool is prevented and the surface finish is enhanced. As discussed in the previous sections, the incorporation of Gr particles acts as a solid lubricant that aids in obtaining a better surface finish. Thus, the SEM investigation confirms the results of the mean S/N plots and ANOVA in optimizing the cutting parameters on the surface roughness of the machined surfaces of the tested materials.

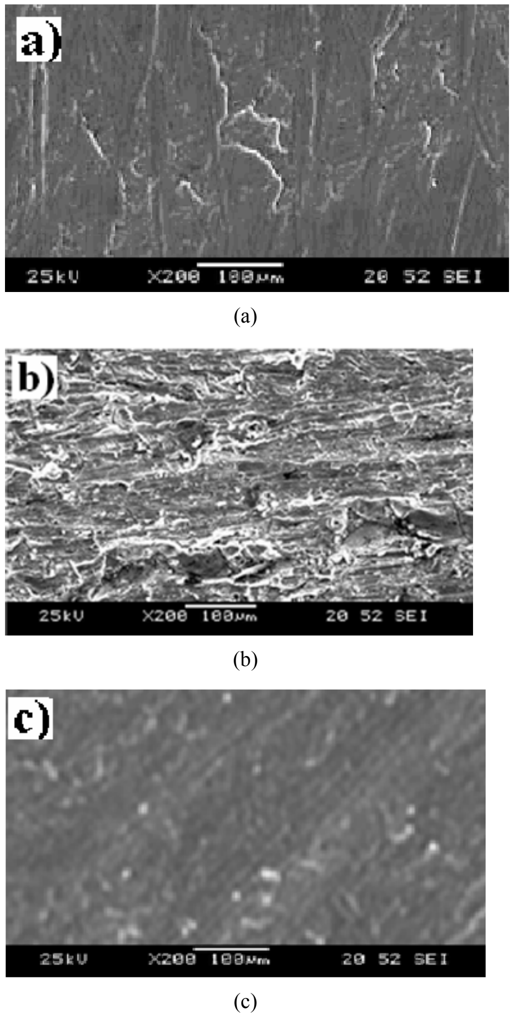


Fig. 7. (a) Scanning electron microscopy (SEM) image of the pure Al after machining; (b) SEM image of the Al-15 wt% fly ash and 1.5 wt% Gr composite before machining; (c) SEM image of the Al-15 wt% fly ash and 1.5 wt% Gr composite after machining.

3.8 Investigation on chip formation

Chip formation during machining is a shear process that involves plastic deformation within the shear zone. The process depends on the machining parameters and properties of the tool and work piece materials. According to theory of metal cutting, studies on chip formation are the most effective and economical way of understanding the machining characteristics of work materials. Dabade and Joshi [19] reported that the size and volume fraction of reinforcement significantly influences the chip formation mechanism during the machining of Al-SiC composites. The physical appearance of chips produced from pure Al, Al-fly ash, and Al-fly ash/Gr composite machined at the optimum parameters are shown in Figs. 8(a)-8(c).

Fig. 8(a) reveals that the chips are long continuous strips during the machining of pure Al. More chip curls with uniform thickness were observed because a higher cutting speed

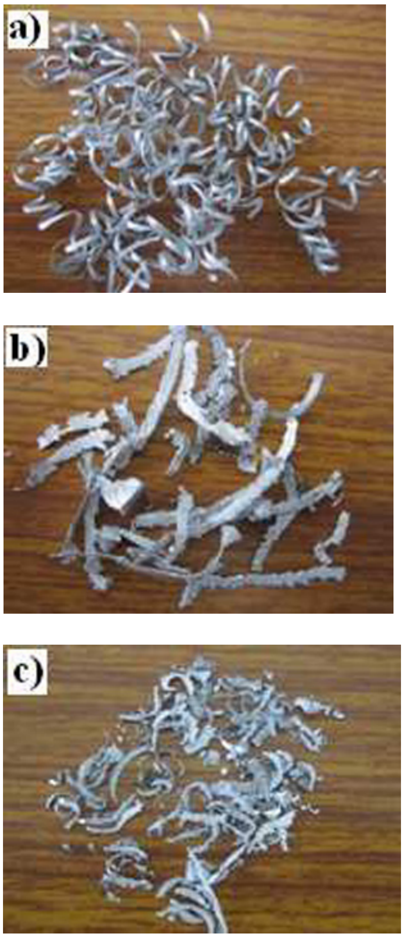


Fig. 8. Chips formed during the machining of (a) pure Al; (b) Al-fly ash composite; (c) Al- fly ash/Gr composite.

enhances the softening of the pure Al.

Semi-continuous chips, which are favorable for enhancing machinability, were produced during the turning of the Al-fly ash composite. Given that the presence of fly ash particles makes the composite relatively brittle, segmented chips are produced. The Al-fly ash composite chips have jagged edges and are wider than pure Al chips. Generally, ductile materials create long spiral chips, whereas chips of brittle materials have little or no tendency to curl. Lin et al. [20] reported that semi-continuous-type chips were observed during the machining of Al-SiCp composites and were attributed to a reduction in the ductility of the work material because of the addition of SiC reinforcement in the composite material.

The chips formed during the turning of the Al-fly ash/Gr (Fig. 8(c)) composites were similar with respect to shape and structure to the Al-fly ash composite chips. However, relatively shorter chips were seen, with jagged edges formed on the outside surface in the case of the Al-fly ash/Gr composites. Similar observations were made by Mohammed T. Hayajneh et al. [21]. They reported that Gr particles dispersed in the metal matrix act as chip breakers and reduce the possibility of the formation of a continuous chip with BUE, which reduces surface roughness. Upon close observation of the chips, we conclude that the pitch of the chip becomes irregular because of the distribution of both the fly ash and Gr particles within the Al matrix.

4. Conclusions

The investigation results show that the feed rate (46.96%) has the highest influence on surface roughness in the machining of an Al-fly ash/Gr composite followed by cutting speed (43.35%) and depth of cut (5.58%). A similar trend was observed in pure Al and Al-fly ash composite. Cutting conditions, such as cutting speed (339.12 m/min), feed rate (0.05 mm/rev), and depth of cut (0.1 mm), can be used to achieve the minimum surface roughness in machining Al, Al-fly ash, and Al-fly ash/Gr composites. The incorporation of 1.5 wt% Gr as supplementary reinforcement decreases the surface roughness of Al-fly ash composites considerably. The confirmation tests show that the error associated with the surface roughness of the tested materials varies by approximately ± 5%. The closeness of the prediction results based on the regression models and experimental values show that the Taguchi experimental technique can be used successfully for both optimization and prediction.

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P. Shanmughasundaram received an AMIE (India) degree in mechanical engineering and an AMIE (India) degree in production engineering from the Institution of Engineers in India, Calcutta. He obtained a Post-Diploma in production engineering from PSG Polytechnic College, Coimbatore. He received a Post Graduate degree in 2004 from Coimbatore Institute of Technology, Anna University, Chennai, Tamil Nadu, India. He is currently pursuing a doctoral degree at Anna University, Chennai. He has published more than 10 articles in international journals. He is a member of ISTE, IE, and SAE. His areas of interest include MMCs, tribology, and optimization techniques.

R. Subramanaian received an M.Tech. in Metallurgical Engineering in 1987 from IIT Kanpur India and a doctoral degree in metallurgical engineering from Bharathiar University in 2001. He is currently working as an Associate Professor in the Department of Metallurgical Engineering, PSG College of Technology, Coimbatore. His areas of specialization are physical metallurgy, powder metallurgy, ODS alloys, MMCs, and material modeling. He has published more than 30 articles in international journals. He is a member of ISTE and IE.