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ORIGINAL ARTICLE

Modelling the effect of surface roughness factors in the machining of 2024Al/Al_2O_3 particle composites based on orthogonal arrays

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Abstract This study presents an experimental investigation of the effects of cutting speed, size and volume fraction of particle on the surface roughness in turning of 2024Al alloy composites reinforced with Al_2O_3 particles. A plan of experiments, based on Taguchi method, was performed machining with different cutting speeds using coated carbide tools K10 and TP30. The objective was to establish a correlation between cutting speed, size and volume fraction of particle with the surface roughness in workpieces. These correlations were obtained by multiple linear regression. The analysis of variance was also employed to carry out the effects of these parameters on the surface roughness. The test results revealed that surface roughness increased with increasing the cutting speed and decreased with increasing the size and the volume fraction of particles for both cutting tools. The average surface roughness values of TP30 cutting tools were observed to be lower than those of K10 tools. For the average surface roughness values of TP30 tool, cutting speed was found to be the most effective factor while the volume fraction of particle was the most effective factor for those of K10 tool. A good agreement between the predicted and experimental surface roughness was observed within a reasonable limit.

Keywords Metal matrix composites · ANOVA · Mathematical modelling · Surface roughness · Taguchi method

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1 Introduction

Metal matrix composites (MMCs) represent a relatively new class of materials characterized by lighter weight and greater wear resistance than those of conventional materials. The particle-reinforced aluminium alloy composites which are among the most widely used composites materials are rapidly replacing the conventional materials in various industrial and engineering applications from automotive to aircraft components. The common applications are bearings, cylinder block linears, vehicle drive shafts, automotive pistons, bicycle frames, etc. because of their improved properties over those of non-reinforced alloys [1–3]. High hardness aluminium oxide (Al_2O_3) or silicon carbide (SiC) particles are commonly used to reinforce the aluminium alloys, but the full application of such MMCs is, however, cost sensitive because of the high machining cost with respect to the hardness and abrasive nature of the reinforcement particles [4, 5].

Machinability of MMCs has received considerable attention because of the high tool wear associated with machining. While great improvements have been shown in the production of near-net-shape MMC products by casting or hot forging, unfortunately, for reasons such as component design and dimensional tolerance requirements, the need for machining cannot be completely eliminated and the resulted near-net-shape products still have to be machined into the designed shape and dimension. Al_2O_3 particle-reinforced MMCs are extremely difficult to machine (turning, milling, drilling, threading) due to their extreme abrasive properties [6, 7]. The presence of the hard Al_2O_3 particles in the aluminium alloy MMCs makes them extremely difficult to machine as they lead to rapid wear of the cutting tools and consequently high tool cost. The primary difficulty when machining MMCs has proven to be short tool life and relatively poor surface finish. Therefore, most of the work regarding MMCs has focused on the study of wear characteristics of various tool materials during machining aluminium alloy composites [5, 7–15]. Tool integrity plays an important role in the form of the machined surface of the workpiece and the control of the cutting quality, and hence research on the characteristics of tool wear is necessary not only for machining the composites but also for improving their application. Investigations on machining of light alloy composites reinforced with Al_2O_3/SiC fibres/particles [4, 16, 17] indicate poor machinability due to abrasive wear of tools. Moreover, quality of the machined surface also deteriorates with tool wear [17]. With existing tools such as cemented carbides coated with titanium nitride (TiN) or titanium carbides (TiC), the wear rate of the tools is so high that machining is extremely expensive. With diamond tools, tool wear is very low but the price is very high and the shaping of the tool is very limited [6].

The issues of machining MMCs have been addressed from various viewpoints. From the available literature on particulate metal matrix composites, it is clear that the morphology, distribution and volume fraction of the reinforcement phase as well as the matrix properties, are all factors that affect the overall cutting properties [18].

The main concern, when machining MMCs, is the extremely high tool wear due to the abrasive action of the ceramic particles. Therefore, materials of very high resistance to abrasive wear are often recommended [16]. The HSS tools are inadequate, cemented carbide tools are preferred for rough machining and PCD tools for finish machining operations [4]. The high cost of PCD tools increases the costs of MMCs machining operations so it becomes necessary to carry out basic machinability studies in order to find cutting conditions using carbide tools, which can result in high productivity at low cost [19].

Taguchi's techniques have been used widely in engineering analysis. The techniques of Taguchi [20, 21] consist of a plan of experiments with the objective of acquiring data in a controlled way, executing these experiments and analyzing data, in order to obtain information about the behaviour of a given process. After the completion of the experiment, the data from all the experiments in the set are analyzed to determine the effect of the various design parameters. Conducting Taguchi experiments in terms of orthogonal arrays allows the effects of several parameters to be determined efficiently and is an important technique in robust design. The treatment of the experimental results is based on the analysis average and the analysis of variance (ANOVA) [20–23].

The aim of the current study, therefore, was to: (a) machine the Al_2O_3 particle-reinforced 2024 aluminium alloy composites produced by a vortex method, with different cutting conditions on a CNC lathe machine using Taguchi method for investigating the wear of cutting tools; (b) measure and evaluate the surface roughness values of the composite materials, using K10- and TP30-coated carbide tools which are having the same geometry but the different coating layers; (c) develop a mathematical model for surface roughness using the cutting speed, size and volume fraction of particles by multiple linear regression for analyzing the cutting parameters, composite characteristics and coating layers of cutting tools influencing the surface roughness. Furthermore, the ANOVA was employed to carry out the effects of various factors and their interactions on the surface roughness. The experimental results were given with a comparison between both cutting tools.

2 Literature review

Several researchers have studied on the machining of MMCs. Channakesavarao et al. [24] have experimented with different cutting tools. They have reported that the crater wear is not appreciable in K10 tools and is having superior wear resistance and produce continuous chips. Hocheng et al. [25] have studied the effect of speed, feed, depth of cut, rake angle and cutting fluid on the chip form, forces, wear and surface roughness. Tool life, surface quality and cutting forces have been studied by Chambers [26]. Yuan and Dong [27] have investigated the effect of percentage volume reinforcement, cutting angle, feed rate and speed on the surface integrity in ultra precision diamond turning of MMCs. El-Gallab and Sklad [13] have used several tool materials to compare its effectiveness. Davim [28] studied the drilling of metal matrix composites based on Taguchi technique to find the influence of cutting parameters on tool wear, torque and surface finish and the interactions between these factors. He analyzed the data by analysis of variance and found the percentage of influence of each factor on responses. Ramulu et al. [29] 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. Davim [30] examined the influence of cutting speed, feed rate and cutting time on turning MMCs (A356/20SiCp-T6) using PCD cutting tools based on the techniques of Taguchi. He established a correlation between cutting speed, feed rate and cutting time with the tool wear, the power consumed and surface roughness. Palanikumar and Karthikeyan [19] investigated the factors influencing surface roughness on the machining of Al/SiC particulate composites using tungsten carbide tool inserts (K10). They have found that the surface roughness of the

Table 1 Characteristics and properties of the materials tested

Material	Volume fraction of Al_2O_3 particles (vol.%)	Average size of Al_2O_3 particles (μm)	Ultimate tensile strength (MPa)	BHN	Density (kg/m^3)
Al-1-16	7.3	16	88	104	2,806
Al-2-16	23.3	16	112	135	2,911
Al-1-66	7.3	66	80	95	2,819
Al-2-66	23.3	66	88	118	2,967

BHN Brinell hardness

composite was highly influenced by the feed rate, cutting speed and volume fraction of SiC particles. Dabade et al. [3] studied the surface integrity as a function of process parameters and tool geometry by analyzing cutting forces, surface finish and microstructure of the machined surfaces on Al/SiC/10p and Al/SiC/30p composites using CBN inserts. Basheer et al. [31] developed a model to predict surface roughness in precision machining of metal matrix composites using PCD tools with respect to size and volume of reinforcement, tool nose radius, feed rate and depth of cut. They have concluded that the size of reinforcements in the composite material influences roughness of the machined surfaces significantly when its magnitude is comparable to that of the feed rate and tool nose radius employed during machining of the composite [32]. Basavarajappa et al. [33] focused the influence of cutting parameters on the drilling characteristics of hybrid metal matrix composites-Al2219/15SiCp and Al2219/15SiCp-3Gr. Their results showed that the dependent variables were greatly influenced by the feed rate rather than the cutting speed for both the composites. Palanikumar and Davim [34] have made an attempt to assess the factors influencing tool wear on the machining of glass fibre-reinforced plastic composites by coated cemented carbide tools using ANOVA technique. The results indicated that cutting speed is a factor, which has greater influence on tool flank wear, followed by feed rate.

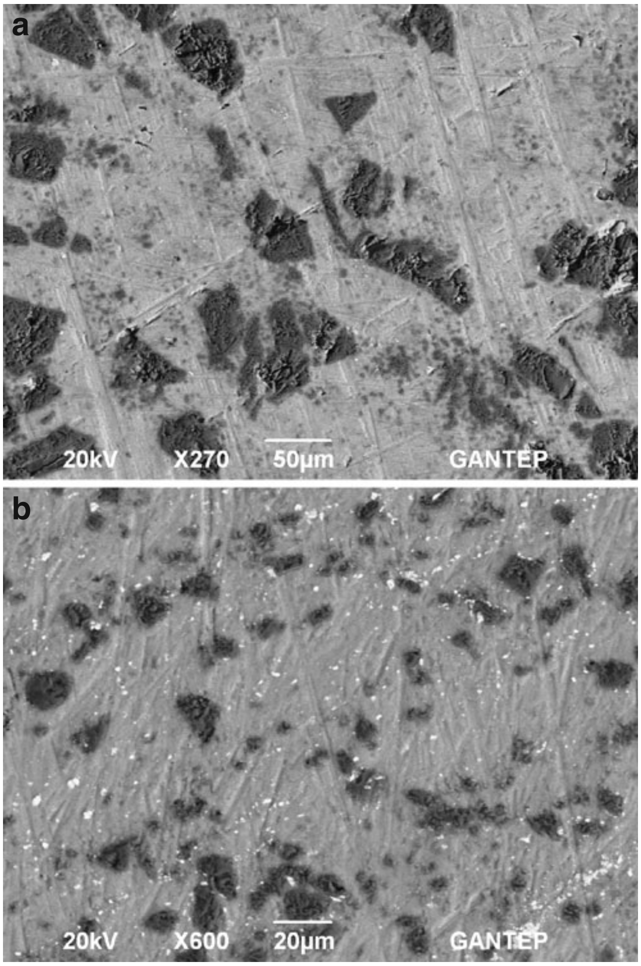


Fig. 1 SEM micrographs of 7.3 vol.% Al_2O_3 particles reinforced composites with particle size of **a** 66 μm, **b** 16 μm; *black regions* are Al_2O_3 particles

Most of the above studies have showed that the wear characteristics of various tool materials based on cutting parameters and surface finish during machining of aluminium-based composites reinforced with SiC particles were investigated. Only the effects of cutting parameters like cutting speed, feed rate and depth of cut have been examined. The effects of size and volume fraction of particles on the surface roughness and tool life have not been studied. However, a limited number of studies on the MMCs reinforced with Al_2O_3 particles have been reported with respect to tool wear, surface finish, particle size and volume fraction of particles using coated cutting tools [6, 29, 35–37]. Therefore, in view of the above, an attempt has been made in this investigation to develop a surface roughness model in terms of cutting speed, size and volume fraction of particle in the machining of the Al_2O_3 particle-reinforced aluminium alloy composites based on orthogonal arrays under various cutting conditions.

Table 2 Designed experimental factors and their levels

Factors	Level 1	Level 2
Cutting speed, V (m/min)	100	210
Particle size, P_s (μm)	16	66
Volume fraction of particle, P_v (vol.%)	7.3	23.3

Table 3 Cutting tool geometry

Tool type	Manufacturer	Rake angle	Clearance angle	Approach angle	Nose radius
K10 cutting too (K10 coated with TiN)	Widia	0°	7°	80° rhombic	0.8 mm
TP30 cutting tool (P30 coated with Ti+Ti (C,N)+TiN)	Seco	0°	7°	80° rhombic	0.8 mm

3 Experimental plan and procedure

3.1 Material details

In this experimental work, 2024 aluminium alloy with the theoretical density of 2,800 kg/m^3 was used as the matrix material while α-Al_2O_3 (alumina) particles various particle sizes of 16 and 66 μm, and a density of 3,950 kg/m^3 were used as the reinforcements. The Al_2O_3 particles supplied by Treibacher, are short particles with a white colour. The grain size of Al_2O_3 particles was determined using a Malvern Laser Size Analyser.

The materials used in the present work were 2024 Al alloy composites reinforced with 7.3 and 23.3 vol.% Al_2O_3 particles, having a composition (in weight percent) of minimum 93 α-alumina, 1.8 TiO_2, and maximum 0.8 Fe_2O_3, 1.1 CaO and 0.2 other magnetic materials. They were fabricated by a vortex method and subsequently applied pressure, using a 2-kW power resistance-heated furnace under protected argon gases [38]. The composites were shaped in the form of a cylinder with a 40-mm outer diameter and height of 140 mm. The chemical composition of the 2024 Al alloy matrix was (weight percent): 3.23 Cu, 0.81 Mg, 0.74 Si, 0.54 Mn, 0.13 Zn and balance Al. Table 1 shows the characteristics and properties of the materials tested in this study. Details of the experimental set-up and production processes are reported in the previous studies [7, 38].

For microstructural investigations, the test samples were prepared by standard metallographic techniques. Microscopic examinations of the specimens were carried out using a scanning electron microscope. The typical microstructures of the Al_2O_3/2024 Al alloy composites are shown in Fig. 1.

3.2 Plan of experiments

The experiments were employed to analyze the effects of testing parameters and characteristics of the materials on surface roughness of the materials when machining MMC workpieces. The Taguchi method for three factors at two levels was used for the elaboration of experiment plans. Table 2 indicates the experimental factors to be designed and their levels. Besides the influences of these factors, the influences of their interactions on the surface roughness were studied as well. The orthogonal array L_8 of Taguchi which has eight rows corresponding to the number tests (7 degrees of freedom) was chosen. The factors and their interactions are assigned to the columns.

The plan of experiments for each cutting tool is made of eight tests (array rows) in which the first column was assigned to the cutting speed (V), the second column to the particle size (P_s) and the third column to the volume fraction of particle (P_v) and the remaining were assigned to the interactions. The response to be studied is the surface roughness (R_a). Moreover, a statistical ANOVA predicted for a 95% confidence level was performed to see which parameters are statistically significant. Finally, a mathematical model of surface roughness for each cutting tool was developed by multiple linear regression.

3.3 Experimental procedure

Machining tests were carried out without coolant and at a constant depth of cut equal to 2 mm and feed rate of 0.1 mm rev^{-1}. Turning tests were conducted to determine the tool wear and surface roughness under different cutting conditions using a 2.2-kW stepless-controlled Boxford 250

Table 4 Orthogonal array of Taguchi for surface roughness (R_a) of K10 and TP30 cutting tools

Test	V (m/min)	P_s (μm)	P_v (vol.%)	R_a (μm) for K10	R_a (μm) for TP30
1	100	16	7.3	1.76	1.05
2	100	16	23.3	0.64	0.66
3	100	66	7.3	0.96	0.58
4	100	66	23.3	0.90	0.72
5	210	16	7.3	1.52	1.10
6	210	16	23.3	0.74	0.87
7	210	66	7.3	1.19	0.94
8	210	66	23.3	1.10	0.93
Means				1.10	0.86

Table 5 Results of the ANOVA for surface roughness (R_a) of K10 cutting tools

Source of variance	SS	DF	Variance	Test F	Statistical P values	Contributions P (%)
V (m/min)	0.01051	1	0.01051	0.61	0.577	1.03
P_s (μm)	0.03251	1	0.03251	1.90	0.400	3.18
P_v (vol.%)	0.52531	1	0.52531	30.70	0.114	51.46
$V \times P_s$	0.04061	1	0.04061	2.37	0.367	3.98
$V \times P_v$	0.01201	1	0.01201	0.70	0.556	1.18
$P_s \times P_v$	0.38281	1	0.38281	22.37	0.133	37.5
Error	0.01711	1	0.01711			1.67
Total	1.02089	7				

SS sum of squares, *DF* degree of freedom

CNC lathe machine when cutting the composites. Two types of cutting tools, including a TiN coated on K10 carbide grade denoted by the term of K10 tool, and a trip-layer coated on P30 carbide grade denoted by the term of TP30 cutting tool in this study, have been used. All tools are commercially available inserts, according to ISO code, CCMT09T308-F1 and CCMT09T308-41 were supplied by Seco and Widia, respectively, for machining tests. Tool geometry used is listed in Table 3.

After each test, the worn cutting tool is measured with the optical tool microscope to determine the degree of flank wear. For these tests, 0.3 mm flank wear (VB) was taken as tool life criteria (according to ISO 3685). The surface roughness (R_a) was measured by using a stylus instrument. For each specimen, the mean of at least five surface roughness measurements was taken as a response variable.

4 Results and discussion

The plan of tests was developed with the aim of relating the effects of the cutting speed (V), particle size (P_s) and volume fraction of particle (P_v) with surface roughness (R_a).

The statistical treatment of the data was made in two phases. The first phase was concerned with the ANOVA and the effects of the factors and the interactions. The second phase was to obtain the correlations between the parameters for surface roughness. Then, the values calculated using all the equations generated for the surface roughness models were compared with the experimental measurements, for the purpose of determining the total average errors for each tool. Lastly, confirmation tests were performed to do a comparison between the foreseen values from the model developed with the values obtained experimentally.

4.1 Analysis of variance

The ANOVA is used to investigate which design parameters significantly affect the quality characteristic. So, it was done an ANOVA of the data using MINITAB version 15 software with the surface roughness (R_a) for analyzing the influence of cutting speed (V), particle size (P_s) and volume fraction of particle (P_v) on the total variance of the results. The orthogonal array of Taguchi used to obtain surface roughness (R_a) is shown in Table 4.

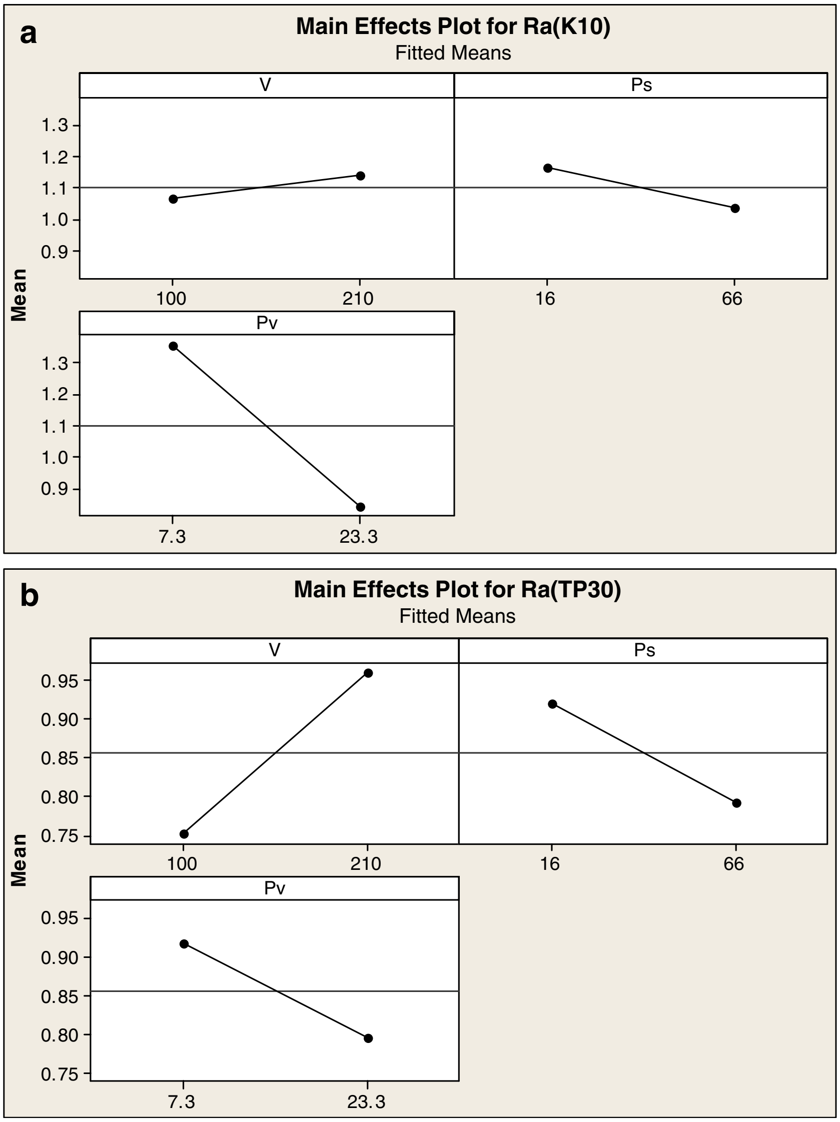
Tables 5 and 6 show the results of the ANOVA for the surface roughness of K10 and TP30 cutting tools, respectively. These analysis were carried out for a level of significance of 5%, i.e. for a level of confidence of 95%. The last column of the tables previously shown indicates the percentage of each factor contribution (P) on the total variation, thus indicating the degree of influence on the result. The main effects and their interaction plots for surface roughness of K10 and TP30 tools are shown in Figs. 2 and 3.

Table 6 Results of the ANOVA for surface roughness (R_a) of TP30 cutting tools

Source of variance	SS	DF	Variance	Test F	Statistical P values	Contributions P (%)
V (m/min)	0.08611	1	0.08611	7.17	0.228	35.44
P_s (μm)	0.03251	1	0.03251	2.71	0.348	13.38
P_v (vol.%)	0.03001	1	0.03001	2.50	0.359	12.35
$V \times P_s$	0.01201	1	0.01201	1.00	0.500	4.94
$V \times P_v$	0.00001	1	0.00001	0.00	0.979	0.004
$P_s \times P_v$	0.07031	1	0.07031	5.85	0.250	28.94
Error	0.01201	1	0.01201			4.94
Total	0.24299	7				

SS sum of squares, *DF* degree of freedom

Fig. 2 Main effects plots for surface roughness (R_a) results of **a** K10 cutting tool and **b** TP30 cutting tool



From the analysis of Table 5 and Fig. 2a, it can be observed that the volume fraction of particle (P=51.46%) had the greatest influence on the surface roughness obtained while the other factors (cutting speed, P=1.03%; size of particle, P=3.18%) had not presented a statistical and physical significance on the surface roughness.

The interaction particle size/volume fraction of particle (P=37.5%) had presented the greatest percentages of statistical and physical significance on the surface roughness after the volume fraction of particle factor (Fig. 3a). However, the other interactions (cutting speed/particle size, P=3.98% and cutting speed/volume fraction of particle, P=1.18%) had not presented a statistical significance on it.

Equally, from the analysis of Table 6, examination of the calculated values of variance ratio (F), which is the variance of the factor divided by the error variance, and percentages of contributions (P%) for all control factors showed a high influence of factor V and low influence of factor P_v on the surface roughness. This is also shown in Fig. 2b. From this table, it can be observed that the cutting speed (P=35.44%), the particle size (P=13.38%) and the volume fraction of particle (P=12.35%) factors had statistical significance on the surface roughness, especially cutting speed. In addition to this, the interaction of the particle size/volume fraction of particle (P=28.94%) had the greatest statistical significance on the surface roughness after the cutting speed factor (Fig. 3b), whereas the other interactions (cutting speed/particle size, P=4.94% and cutting speed/volume fraction of particle, P=0.004%) had no statistical significance because their percentages of contributions are smaller than error associated (P=4.94%) at 95% confidence level.

As a result, from the ANOVA tables it can be shown that the error associated was approximately 1.67% for surface roughness of K10 cutting tool and 4.94% for the surface roughness of TP30 cutting tool. Moreover, it could be seen clearly in Figs. 2 and 3 that in general the surface roughness

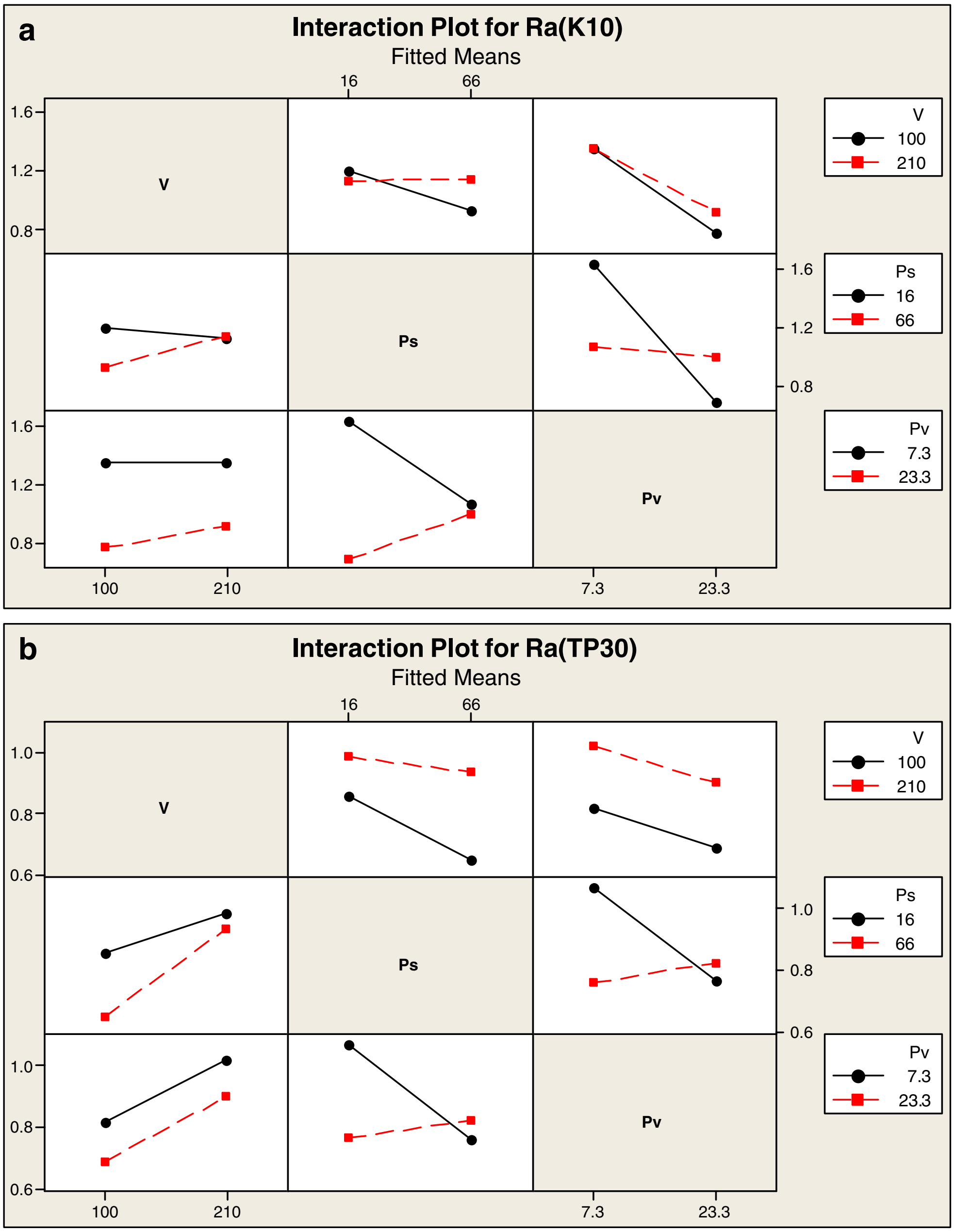


Fig. 3 Interaction plots for surface roughness (R_a) results of **a** K10 cutting tool and **b** TP30 cutting tool

values of the workpieces for both cutting tools increased with increasing the cutting speed and, decreased with increasing the size and volume fraction of particles.

4.2 Development of predictions methods

Considering the surface roughness values as output and the factors (cutting speed, size and volume fraction of particle) as inputs; it is possible to attain a linear model equation expressing the relationship between the output and inputs. The correlations between the factors and the measured surface roughness were obtained by multiple linear regression.

When a regression analysis is performed utilizing the least squares method to the experimental data in order to obtain the coefficients of this equation, the following two equations (one equation for each cutting tool) are established:

$$R_{a(K10)} = 2.82 - 0.00281V - 0.0273P_s - 0.0905P_v + 0.000052V{*}P_s + 0.000088\mathrm{V}{*}P_v + 0.00109P_s{*}P_v \quad \left(R^2 = 0.98\right) \tag{1}$$

$$R_{a(TP30)} = 1.27 + 0.00069V - 0.0141P_s - 0.0273P_v + 0.000028V{*}P_s + 0.000003V{*}P_v + 0.000469P_s{*}P_v \quad \left(R^2 = 0.95\right) \tag{2}$$

Table 7 Surface roughness values and total average errors for each tool

Test	Surface roughness, R_a (μm) for K10			Surface roughness, R_a (μm) for TP30		
	Experiment	Model (Eq. 1)	Error (%)	Experiment	Model (Eq. 2)	Error (%)
1	1.760	1.716	2.48	1.050	1.016	3.25
2	0.640	0.688	7.52	0.660	0.704	6.66
3	0.960	1.009	5.12	0.580	0.622	7.25
4	0.900	0.853	5.22	0.720	0.685	4.82
5	1.520	1.569	3.25	1.100	1.143	3.95
6	0.740	0.696	5.93	0.870	0.836	3.81
7	1.190	1.148	3.51	0.940	0.903	3.87
8	1.100	1.146	4.27	0.930	0.972	4.54
Total average error			4.66			4.77

The values calculated using the equations generated for surface roughness predictions were compared with the experimental results, for the purpose of determining the percentage errors of predictions. The values of percentage errors for each cutting tool are given in Table 7. From this table, it can be shown that total average error is 4.66% for K10 cutting tool while it is 4.77% for TP30 cutting tool.

Figure 4 also shows a comparison of regression equations with experimental surface roughness results of the K10 and TP30 cutting tools for all kinds of the composite materials. As shown in this figure, generally surface roughness obtained by experimentally and predicted equations increased with increasing the cutting speed for both cutting tools while it decreased with increasing the size and volume fraction of particles. Only, it was observed that surface roughness of the K10 cutting tool for Al-1-16 composite decreased with increasing the cutting speed. On the other hand, for the 23.3 vol.% Al_2O_3 particles reinforced composites, the surface roughness values of both tools increased with increasing the particle size since the fractured particles resulted in more damage to the alloy matrix. However, it was shown that R_a values decreased with increasing the particle size for the other composites. For all of the materials, the average surface roughness values of the TP30 tools were found to be lower than those of the K10 tools. The least surface roughness values were obtained in the machining of the Al-1-66 composite at 100 m/min cutting speed for TP30 tool while the highest surface roughness was found for the machining of the Al-1-16 composite at the same cutting speed for K10 tool. Also,

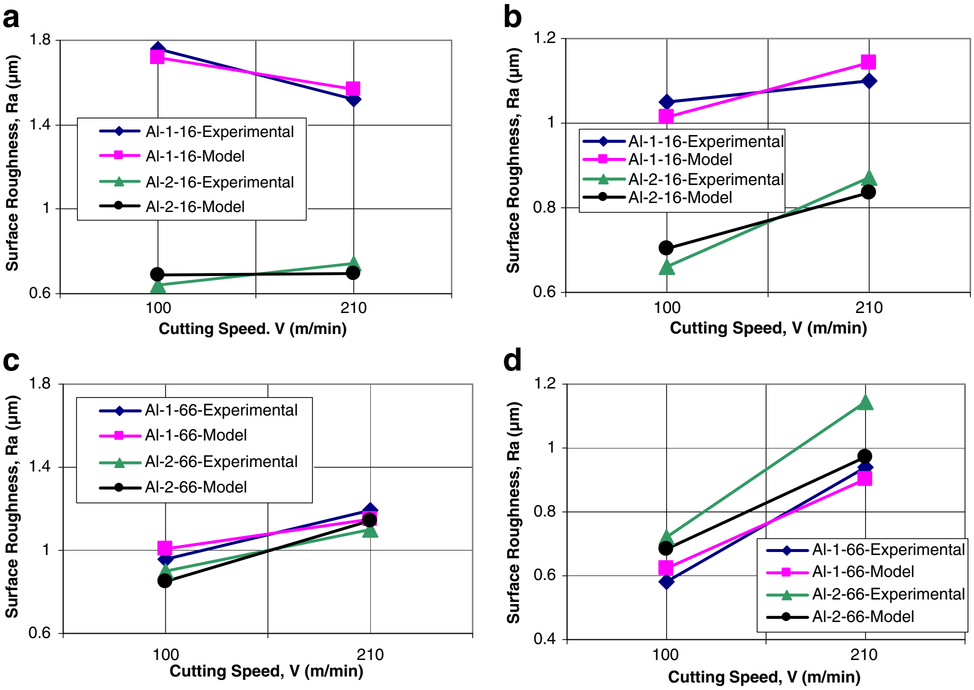


Fig. 4 Comparison of models with the experimental average surface roughness (R_a) values of composites with particle size of **a** 16 μm, **b** 66 μm for K10 cutting tool, **c** 16 μm, **d** 66 μm for TP30 cutting tool

Table 8 Cutting speed, size and volume fraction of particles used in the confirmation tests

Test	V (m/min)	P_s (μm)	P_v (vol.%)
1c	160	66	7.3
2c	185	16	15
3c	130	66	23.3

from this figure, it can be observed that the difference between the surface roughness values of the composites reinforced with the size of 16-μm particle was more than that of the composites reinforced with the size of 66-μm particle for both cutting tools.

There is no doubt that the data gathered through the experiments possesses some errors and this fact influences the predictions obtained. Because actual cutting speed was lower than desired cutting speed which could not be used in the machining actually. During turning operations, rotational speed should be adjusted to keep cutting speeds constant because of the decreasing diameter of workpiece being machined. Only cutting speed was selected, and adjustment of rotational speed was performed automatically during the machining on the CNC lathe machine used in this study. However, cutting speed could not be kept constant due to fluctuating of the rotational speed. This could be attributed to the different characteristics, structures and hardness of the particle-reinforced composite materials at substrate, work hardening of machined surface and abrasion of tool. So, there was a difference between desired and actual cutting speeds. Although the error associated between the experiments and predictions is seen clearly from Fig. 4, the models generally give good results in all cases. This indicates the reliability of the surface roughness predictions established.

4.3 Confirmation tests

Table 8 shows the cutting speed, size and volume fraction of particles used in the turning confirmation tests which were performed under the same cutting conditions with the experimental tests. Table 9 presents the results of the confirmation tests obtained where a comparison was carried out between the calculated values from the model equation developed in this study (Eqs. 1 and 2), with the experimental values.

From the analysis of the confirmation tests shown in Table 9, it can be observed that the calculated error is greater for the surface roughness (R_a) of the K10 cutting tool (maximum value 17.78% and minimum 9.76%) than for that of the TP30 cutting tool (maximum value 11.03% and minimum 4.86%). This error may be due to the different characteristics and structures of the materials tested. Therefore, it can be considered that Eqs. 1 and 2 correlate the evolution of the surface roughness based on the cutting speed, size and volume fraction of particles with a reasonable degree of approximation.

5 Conclusions

The Taguchi method was adopted and ANOVA analysis was performed to investigate the effects of cutting speed, size and volume fraction of particle on the surface roughness in the machining of Al_2O_3 particle-reinforced aluminium alloy composites. The mathematical models of surface roughness were predicted by multiple linear regression due to these parameters. The following conclusions have been drawn from the results of this experimental work:

1. 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.
2. It was observed that the cutting speed (35.44%) was the most effective factor which had the greatest physical as well as statistical influence on the surface roughness followed by the size and volume fraction of Al_2O_3 particles (13.38% and 12.35%) for TP30 cutting tool. However, for the K10 tool the volume fraction of particle (51.46%) was found to be the most effective factor followed by the interaction of the particle size/ the volume fraction of particles (37.5%).
3. The error associated to the ANOVA table (1.67% and 4.94% for K10 and TP30 tools, respectively) for the factors and the surface roughness models obtained by the multiple linear regression (correlation coefficient of 0.98 and 0.95, and the mean absolute error of 4.66%

Table 9 Confirmation tests results and comparison with calculated values

Test	Surface roughness, R_a (μm) for K10			Surface roughness, R_a (μm) for TP30		
	Experiment	Model (Eq. 1)	Error (%)	Experiment	Model (Eq. 2)	Error (%)
1c	0.97	1.085	11.86	0.74	0.776	4.86
2c	0.99	1.166	17.78	0.87	0.966	11.03
3c	0.85	0.933	9.76	0.70	0.764	9.14

and 4.77% for K10 and TP30 tools) showed that the satisfactory correlation was established. Also, it was observed that there was a good agreement between the predicted and experimental data.

4. The mean error indicated that the error associated to the surface roughness for TP30 tool (maximum value 11.03% and minimum 4.86%) was lower than that for K10 tool (maximum value 17.78% and minimum 9.76%).

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