



PERFORMANCE EVALUATION OF COATED CARBIDE INSERTS ON DRY MACHINING OF AL-B₄C METAL MATRIX COMPOSITES USING TAGUCHI'S ROBUST DESIGN AND WEIGHTED GREY ANALYSIS

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ABSTRACT

This paper presents the fabrication and machinability assessment of aluminum metal matrix composites (Al-MMC). Boron carbide (B₄C) particles having average size of 37 μm is dispersed in 6061-T6 matrix alloy. The composite bar was fabricated through mechanical assisted stir casting method. Machining experiments based on Taguchi's L9 orthogonal array was conducted under dry condition using multi-layer coated carbide insert (TiN/Al₂O₃/TiCN/TiN). Machinability indices such as surface roughness (R_a , R_t and R_z) and cutting force (F_z) were considered as response measures. The results obtained from experiments were analyzed to predict the optimal machining conditions using Taguchi single objective approach. From the statistical analysis it was found that the feed rate is the most influencing factor for both surface roughness and cutting force followed by depth of cut. The developed mathematical model shows that the experimental and predicated results are very close to each other. Finally, the single optimal process parameter combination was found using weighted grey analysis (WGA) and the optimal results are verified through confirmation experiment.

Keywords: Al-B₄C metal matrix, machinability, surface roughness, Taguchi technique, coated carbide tool, weighted grey analysis.

INTRODUCTION

The utilization of metal matrix composites materials (MMCs) in the field of aerospace, defense and automobile industries are being increased now-a-days because of their enhanced mechanical properties such as high hardness, tensile strength at both room and elevated temperatures, wear resistance combined with low density over unreinforced alloys [1-4]. The most used matrix materials are aluminium, magnesium, titanium and copper. For the fabrication of MMCs, these alloys are used as matrix materials and fibers, whiskers and ceramic particles are used as reinforcements [5]. However, the particulate metal matrix composites are identified as potential green materials for various applications due to their advantageous thermo-mechanical properties such as low coefficient of thermal expansion, high ultimate tensile strength, high impact strength, and hardness [6, 7, and 8]. Generally SiC, Al₂O₃ and graphite particles are widely being used as reinforcements. These ceramic particulate MMCs exhibits improved tribological properties combined with low density and lighter in weight and finds application in cylinder blocks, pistons, brake disks and calipers [9, 10]. However, the strength and properties of ceramic particulate reinforced composites depends on the type and size of the reinforcement, volume fraction, coarse/fine of the reinforced particles, morphology and its distribution [11, 12, 13, 14, 15, and 16].

From the contributions of several researchers in the past, some suitable methods for the fabrication of these composites are powder metallurgy, spray atomization and co-deposition, plasma spraying, stir casting and squeeze casting [10]. Among the several fabrication techniques available for the development of MMCs, stir casting method being utilized in recent years due to economic and technological advantages. But, these composites are processed to near net shape, subsequent machining is

unavoidable for converting in to engineering products. Literature reveals that most of the researchers are used Al 356, 2014, 6061 and 7075 aluminium metal matrix reinforced with SiC particles. SiC particles used in aluminum metal matrix are harder than tungsten carbide which has many problems in machining such as rapid tool wear, adverse effect of surface quality, increased cutting force and power consumption [18].

From early studies on these composites, [19-20], it is reported that the tool wear is excessive and surface finish is very poor while cemented carbide tip tools are used for machining. The hard particles in MMCs which intermittently come into contact to the top surface of MMC and these particles act as small cutting edges, which resulted in abrasion wear on the cutting tool in due course and resulting in the formation of poor surface finish. In addition built-up edge (BUE) is formed during turning [15]. The principal dominant tool wear on flank face was found to be abrasion [21]. From contribution of the several researchers, it is concluded that polycrystalline diamond tools (PCD) are considered the most effective and preferred as best candidate for the machining of MMCs [22]. However the relatively high cost factors associated with such tools has forced to look for relatively low cost cutting tool materials to perform in an acceptable range. Coated carbide tools is the proposed alternative in this regard due to its low cost compared to PCD and at the same time, it improves the economics of machining process. Sahin et al investigated the effect of coating on tool life and surface roughness on dry machining of MMCs and reported that in the multi-layer coating the top layer should be TiN [23]. While the coatings revolutionized the life span of cutting tools, the extent of their effectiveness differs across different manufacturers [24]. Different coatings have been introduced in order to improve the cutting tools performance. In order to justify



the applicability of multilayer coated carbide inserts in machining particulate metal matrix composite, it is necessary to investigate several machinability aspects in detail.

Among the various series of aluminium alloys, heat treatable Al 6xxx and Al 7xxx series have been much explored in recent days. In particular Al 6061-T6 alloy is highly corrosion resistant and exhibits moderate strength and finds many applications in the construction, automotive and marine fields [25-27]. These composites have better wear resistance and high temperature stability as compared to A356 and 2xxx series Al alloys. Very few works has been reported so far about the machining of aluminium 6061-T6 matrix composites reinforced with B₄C particles. From the review of literature it was found that no work has been reported to study the effect of multi-layer coated carbide insert for machining MMCs.

Therefore, the objective of present work is focused to study the performance of multi layered coated carbide insert (TiN/Al₂O₃/TiCN/TiN) on dry machining of Al 6061-B₄C MMCs using Taguchi's design of experiments. Two response measures like surface roughness and cutting force were analyzed. The regression model was developed to predict the optimal results. Analysis of variance is used to analyze the significant effect of parameters on the responses. Multi-response optimization of process parameters was carried out using weighted grey analysis (WGA) industrial manufacturing conditions.

EXPERIMENTAL WORK

Fabrication of MMCS

In this work, the Al 6061 alloy is used as matrix and B₄C particles as reinforcement for the preparation of composites. Among the various reinforcements, B₄C is used due to its attractive properties such as high hardness as compared to SiC (2700 KH) and Al₂O₃ (2100 KH) and lighter (2.52 g/cm³) than SiC and Al₂O₃ (3.20 and 3.96 g/cm³). The composite bars of diameter 30mm and length 250mm are fabricated through mechanical assisted stir casting method. To improve the wettability and controlling the interface layer between Aluminium and B₄C, the magnesium is added on 1:1 ratio basis. Before introducing reinforcement particles into the melt they were preheated to a temperature of 250°C- 450°C. Argon gas is supplied in the furnace for a period of 5 min to have inert atmosphere of the composite mixture. A pouring temperature of 750°C was adopted and the molten composite was poured into permanent steel moulds. Microscopic examination of the developed composites was carried out using optical microscope. Figure-1 shows the micrograph of Al-B₄C MMC and it ensures the uniform dispersion of the reinforcements in the matrix alloy.

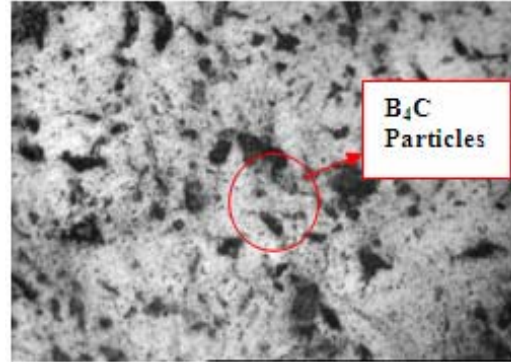


Figure-1. Optical micrograph image of Al-B₄C composites.

Table-1. Parameters and their levels.

Parameter, symbol	Units	Levels		
		1	2	3
Cutting speed	m/min	80	100	120
Feed rate	mm/rev	0.103	0.206	0.294
Depth of cut	mm	0.3	0.6	0.9

EXPERIMENTAL SETUP

The fabricated composites was dry turned on a medium duty lathe having a spindle speed of 1600 rpm and a drive motor power of 7.5 kW. The experiments were performed as per Taguchi's L9 orthogonal array of experimental design. Cutting speed, feed rate and depth of cut factors are taken as control factors and each varied at three levels as listed in Table-1. The composites was turned using a grade of TN 8135 CVD multi-layer coated carbide insert. The ISO grading for inserts was CNMG 120408- FR (TiN/Al₂O₃/TiCN/TiN) having negative rake angle nose radius of 0.8 mm. Cutting force was measured using 9121 type Kistler dynamometer with digital indicator connected to a data acquisition system. The surface roughness was measured using Mhar surf test with the cut-off 1.75 mm. The three surface roughness parameters were measured for surface characteristics i.e. arithmetic surface roughness average (R_a), maximum peak-to-valley height within sampling length (R_z) and maximum peak-to-valley height within assessment length (R_t). The measurement was taken at three locations (90° apart) around the circumference of the work piece and the average values were recorded.

RESULTS AND DISCUSSIONS

The following section discuss about the performance evaluation of machining parameters and its effects on surface roughness (R_a , R_t and R_z) and cutting force (F_z) on dry turning of Al-B₄C composites.

ANALYSIS OF EXPERIMENTAL DATA

Table-2 presents the experimental results of surface roughness and cutting force for the machined



surface for various cutting conditions. Figure-2 shows the interaction plot between cutting speed (v) vs depth of cut for F_z . It is evident from the Figure-2, that the cutting force increases rapidly at higher depth of cut (0.9mm) when compared to low depth of cut (0.3 mm). Experimental results reveals that when the depth of cut is increased from 0.3 to 0.9 mm, the cutting force goes up to 2.61 times compared to its value at lower depth of cut (trial 1 and trial 7) but the variation of cutting force with cutting speed is very small. From the experimental results,

depth of cut was found to be significant factors to affect the cutting force as compared to cutting speed. Hence it is better to increase cutting speed rather than feed rate or depth of cut while machining of this composites by taking cutting force into under consideration. The higher cutting force is observed at trial 3, 5 and 7 is due to high depth of cut and low thermal conductivity of developed composites. The built-up-edge formation is observed at the trial 3, 5 and 7 i.e. extreme conditions of feed rate and depth of cut.

Table-2. Shows the experimental results of surface roughness and cutting force.

Trial No	Process parameters and its levels			Experimental results			
	v m/min	f mm/rev	d mm	R_a μm	R_t μm	R_z μm	F_z μm
1	80	0.103	0.3	1.801	8.716	10.608	46.29
2	80	0.206	0.6	2.328	11.568	15.522	50.39
3	80	0.294	0.9	2.476	12.166	15.245	113.8
4	100	0.103	0.6	1.672	7.386	9.493	32.52
5	100	0.206	0.9	2.305	9.092	12.562	106.6
6	100	0.294	0.3	2.778	15.995	22.331	52.15
7	120	0.103	0.9	1.757	8.174	11.032	121
8	120	0.206	0.3	2.495	9.523	12.568	38.38
9	120	0.294	0.6	3.089	15.440	21.372	61.23

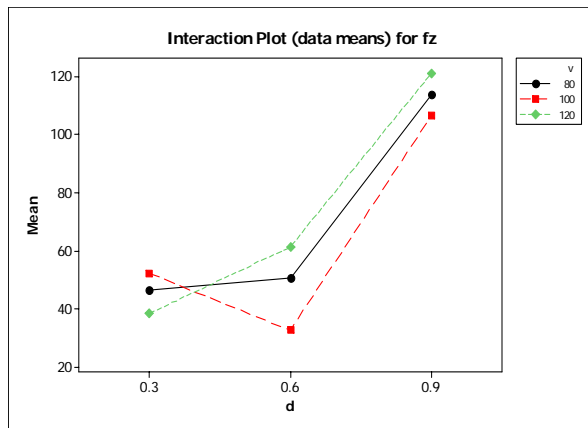


Figure-2. Interaction plot between cutting speed (v) vs depth of cut for F_z .

This indicated the cutting temperature produced by the coated carbide inserts is higher for the above trials. This kind of built-up-edge formation is not observed for other trials. Figure-3 indicates the interaction plot for feed rate V_s surface roughness (R_a) for different levels of cutting speed. For all the surface roughness criteria (R_a , R_t and R_z), the roughness found to increase at with feed rate but at slower rate up to 0.206 mm/rev. At higher feed rate of 0.294 mm/rev, the surface roughness deteriorates rapidly. A feed mark on the machined surface is observed at higher feed rate which indicated that the surface quality is deteriorates rapidly. And also the increase in feed

increase in feed resulted in vibration and chatter which consequently led to higher surface roughness. From the experimental results, it was proven that feed rate is the most influence factor for the machined surface quality. The test results shows that all the surface roughness criteria (R_a , R_t and R_z) has lower roughness values at higher cutting speed when compared to low cutting speed. This is due to the machining system less prone to chatter and vibration at higher cutting speed which led to better surface finish.

Similarly for the surface roughness criteria for all measures are within the limit of 2 μm in all the trials. This indicated that better machining has been observed using multilayer coated carbide insert ($\text{TiN}/\text{Al}_2\text{O}_3/\text{TiCN}/\text{TiN}$)

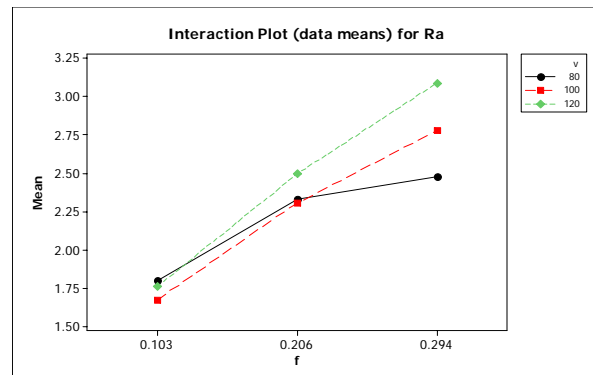


Figure-3. Interaction plot between feed rate and cutting speed for surface roughness.



in dry turning of Al-B₄C composite. This may be attributed due to the presence of wear resistance coating of TiCN. It helps in the delaying the progression of flank wear in machining. In addition, the top layer of TiN protects the cutting edge from diffusion wear and Al₂O₃ layer act as a barrier for the tool wear progression in machining. Finally, this combination of four layers coating on the carbide insert especially Al₂O₃ at intermediate helps to machining the composites at high cutting speed and also enchaining the machining at extreme parameter conditions.

TOOL WEAR

The turning tests were performed on composite bar to evaluate the wear resistance of multi-layer coated carbide inserts. Nine fresh cutting edges were selected according to Taguchi's L9 orthogonal array and 30 mm is used as machining length. After machining of Al/B₄C composite using coated carbide inserts, the flank wear of the worn out tool tip was measured according to ISO 3685 with a Mitutoyo optical microscope using a 50 µm magnification and 1mm resolution. The worn out image of the cutting inserts at the tool tip for maximum cutting force in trial is shown in Figures 4, 5 and 6. It was observed from the tool tip that the dominant wear type in dry turning was abrasion and also built-up-edge formation. From the observations, there is no edge chipping or fracturing is found after machining. However, a detail studies on the effectiveness and potential of the given coated inserts, parametric optimization and mathematical model study is essentially required for all surface roughness criteria and cutting force individually and simultaneously. The detailed analysis pertaining to above has been discussed in following sections.

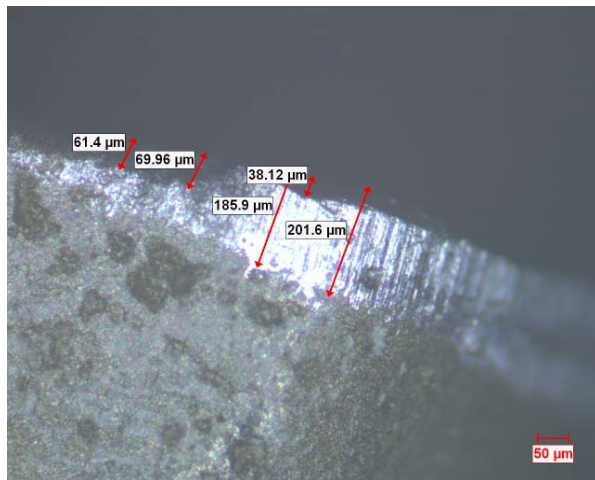


Figure-4. Tool wear analysis for Trial 3.

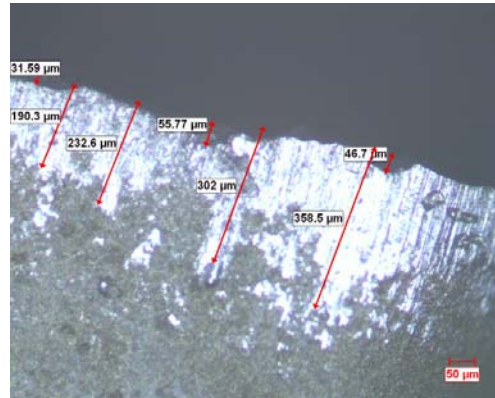


Figure-5. Tool wear analysis for Trial 5.

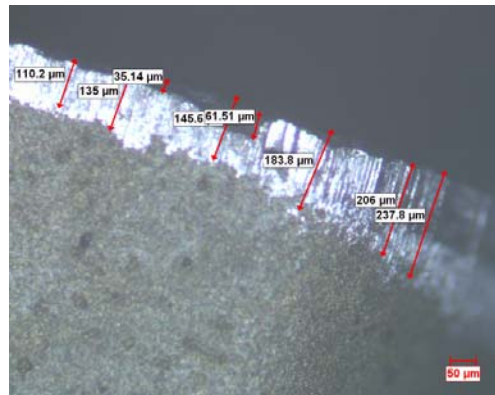


Figure-6. Tool wear analysis for Trial 7.

DEVELOPING OF MATHEMATICAL MODEL

A multiple linear regression model was carried to correlate between the dependent variable (R_a , R_t , R_z and F_z) and predictors (cutting speed, feed rate depth of cut) at 95% confidence level by considering input parameters. By taking experimental data, least square method is applied to determine the regression co-efficient of equation. In addition to linear regression equations and coefficient of determination (R^2) has been utilized to study the significance of regression model developed. Usually, the R^2 value lies in the range of 0 to 1 (i.e. $0 \leq R^2 \leq 1$). When R^2 value approaches to unity, it is taken as better prediction of responses and fitting of the model with the experimental data. If R^2 value is 85%, it means that this model explains about 85% of the variability in predicting new observations. Therefore, the following regression equations are obtained for both cutting force and surface roughness.

$$R_a = 0.769 + 0.00613 v + 5.45 f - 0.298 d \quad (1)$$

$$R^2 = 95\%$$

$$R_z = 5.23 + 0.0057 v + 33.3 f - 2.67 d \quad (2)$$

$$R^2 = 85\%$$

$$R_t = 4.09 + 0.0300 v + 48.0 f - 3.70 d \quad (3)$$

$$R^2 = 83\%$$

$$F_z = -16.7 + 0.084 v + 46.0 f + 114 d \quad (4)$$

$$R^2 = 94\%$$



The model presented has significant co-efficient R^2 value which explaining 95% for R_a , 85% for R_z , 83% for R_t and 94% for F_z . This helps to indicate the model is highly significant and also the experimental results and predicated values for the responses criteria are very close to each other. Experimental and predicated values for all response are listed in Table-3. Therefore, the developed regression models can be used to predict the value of responses of the machining process.

MULTI-RESPONSE OPTIMIZATION

In this research work, the weighted grey analysis (WGA) is used to study the multiple machinability characteristics into the equivalent single performance characteristics of developed composites mixture. It was observed from the experimental results (Table-3) that for a good surface quality low cutting speed, low feed rate and high depth of cut for R_a and R_t and for R_z medium cutting speed. Similarly for cutting force F_z , medium speed, low feed rate and low depth of cut. However, the cutting force accelerates with increase in depth of cut and consequently accelerated the flank wear which becomes unsatisfactory for above mentioned cut conditions. Form interaction plot, feed is the most influence factor for surface roughness

criteria and depth of cut for cutting force. Thus, it is need to have a single solution to this problem. In order evaluate the performance of multi-layer coated carbide insert in dry machining of composite mixture and converting a multi responses in single response, a taguchi based a multi parametric optimization is needed. In this study, a Taguchi based weighted grey analysis is used. The following are the guidelines are used to perform the optimization of composite machining process parameters: i) Data pre-processing- Normalize the experimental data between 0 and 1 called grey relational generation (Table-4) which includes all the performance characteristics by considering lower the better characteristics; ii) calculate the Grey relational coefficient to express the relevancy between the ideal and actual normalized experimental results and grade is obtained by averaging the grey relation coefficients for all the measures. While calculating the grey relational coefficient, the distinguishing coefficient (ϵ) which usually defined in the range between 0 and 1. The value ϵ is usually assumed to 0.5 for the responses. In this work, the responses consider here are four different performance characteristics. So, in order to give weights for all the response, a simple approach based on the Eigen values

Table-3. Shows the experimental results vs Predicated results.

Trial	Experimental results				Predicated results			
	R_a	R_t	R_z	F_z	R_a	R_t	R_z	F_z
1	1.801	8.716	10.608	46.29	1.7289	8.3149	10.324	38.958
2	2.328	11.568	15.522	50.39	2.2009	10.9438	14.158	67.896
3	2.476	12.166	15.245	113.8	2.6020	13.1398	17.368	106.236
4	1.672	7.386	9.493	32.52	1.7615	7.6279	9.814	64.838
5	2.305	9.092	12.562	106.6	2.2335	10.2568	13.648	103.776
6	2.778	15.995	22.331	52.15	2.9028	14.8558	20.188	39.516
7	1.757	8.174	11.032	121	1.7941	6.9409	9.304	100.718
8	2.495	9.523	12.568	38.38	2.5343	11.9728	16.468	37.056
9	3.089	15.44	21.372	61.23	2.9245	14.1022	19.582	75.304

Table-4. Normalized data and Δo_i for each of the responses.

Trial	Normalized data				Evaluating Δo_i			
	R_a	R_t	R_z	F_z	R_a	R_t	R_z	F_z
1	0.9090	0.8455	0.9131	0.8444	0.0910	0.1545	0.0869	0.1556
2	0.4630	0.4858	0.4696	0.2020	0.4629	0.5142	0.5304	0.7980
3	0.4326	0.4448	0.5520	0.0814	0.5674	0.5552	0.4480	0.9186
4	1.0000	1.0000	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000
5	0.5533	0.8018	0.7609	0.1627	0.4467	0.1982	0.2391	0.8373
6	0.2195	0.0000	0.0000	0.7781	0.7805	1.0000	1.0000	0.2219
7	0.9400	0.9085	0.8801	0.0000	0.0600	0.0915	0.1199	1.0000
8	0.4192	0.7518	0.7605	0.9338	0.5808	0.2482	0.2395	0.0662
9	0.0000	0.0645	0.0747	0.6755	1.0000	0.9355	0.9253	0.3245

**Table-5.** Grey relation coefficient and grade.

Trial	Grey relation coefficient				Grey relational grade	Rank
	R_a	R_t	R_z	F_z		
1	0.8460	0.7640	0.8520	0.7626	0.8255	3
2	0.5193	0.4930	0.4853	0.3852	0.5113	6
3	0.4684	0.4738	0.5274	0.3525	0.4716	7
4	1.0000	1.0000	1.0000	1.0000	1.0000	1
5	0.5281	0.7162	0.6765	0.3739	0.5799	4
6	0.3905	0.3333	0.3333	0.6927	0.3748	8
7	0.8929	0.8453	0.8066	0.3333	0.8769	2
8	0.4626	0.6682	0.6761	0.8830	0.5221	5
9	0.3333	0.3483	0.3508	0.6064	0.3382	9

of the principal components was used to calculate the grey grade. iii) Analysis the experimental results using the grey relation grade and statistical ANOVA iv) select the optimum levels of process parameters from response Table.

The normalized data, calculation of Δ_{oi} , grey relational coefficients and grey relational grade for each experiment using L9 orthogonal array is given in Tables 4, 5 and 6. The value 1 (Table 5) i.e. higher grey relational grade represents that the corresponding experimental result is closer to the ideally normalized value. In other words, optimization of the complicated multiple performance characteristics can be converted into optimization of a single grey relational grade. Since the experimental design is orthogonal, it is then parameter on the grey relational grade at different possible to separate out the effect of each machining levels. The grey relational grade graph for the levels of the machining parameters is shown in Figure-7 and Table-7. The mean grey relational grade value is less in the region of high cutting speed and feed compared to medium cutting speed and low cutting feed. This indicated that at higher value of feed rate the surface roughness and cutting force will be high and tool flank wear will be less. Basically, the larger the grey relational grade, the better is the multiple performance characteristics. Based on the interpretation of mean grey relational grade at each level of the parameters, the optimal machining parameters are the cutting speed at level 2, feed at level 1, and depth of cut at level 3 (A2B1C3). Based on results of analysis of variance for the grey relational grade value, the feed rate with 62% of contribution is the most significant machining parameter for the simultaneous optimization of surface roughness and cutting force on dry turning operation followed by the depth of cut with 12.6% and cutting speed of 7.28%. Based on the analysis, the optimal machining parameters are the cutting speed at level 1(100 m/min), feed at level 1 (0.103mm/rev), and depth of cut at level 2 (0.6 mm) i.e. A2B1C2. However, relative importance among the machining parameters for the multiple performance characteristics is still needs to be known so that the

optimal combinations of the machining parameter levels can be determined more accurately. From confirmation experiment, the predicted and experimental grey relational grade is very close to each other. Table-8 list experimental and predicated results of confirmation test.

Table-6. ANOVA results for grey relation grade.

Source	DF	SS	MS	F	P	P %
v	2	0.00820	0.00410	0.85	0.541	7.28
f	2	0.40820	0.20410	3.84	0.207	62.0
d	2	0.00719	0.03597	0.49	0.672	12.6
Error	2	0.01290	0.04310			
Total	8	0.43649				

Table-7. Response table for mean grey relation grade.

Source/ level	v	f	d
1	0.6028	0.9008	0.5742
2	0.6516	0.5378	0.6165
3	0.5791	0.3949	0.6428
Delta	0.0725	0.5059	0.0686
Rank	2	1	3

Table-8. Results for confirmation results.

	Initial machining process parameters	Optimal process parameters
Factor level/ Responses	A1B1C1	A2B1C3
Ra	1.801	1.582
Rt	8.716	7.125
Rz	10.608	9.234
Fz	46.29	48.54

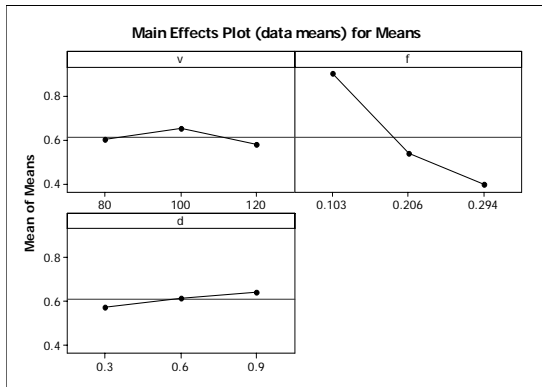


Figure-7. Mean effect plot for grey relational grade.

CONCLUSIONS

This paper presented a detailed study on the dry machining of Al/B₄C using multilayer coated carbide insert. Taguchi L9 orthogonal array, mathematical model and Taguchi based weighted grey analysis (WGA) was adopted for finding the optimal process parameter for cutting force and surface roughness. The following conclusions were drawn from the research paper:

- From interaction plot, the higher cutting force is observed with increase in depth of cut. Higher cutting force up to 2.61 times is observed at higher depth of cut (0.9 mm) when compared to low depth of cut (0.3 mm).
- From interaction plot, surface roughness criteria are found to increase with increase of feed but at slower rate up to 0.103 mm/rev. At 0.294 mm/rev feed, the roughness value deteriorated rapidly. It is also observed that surface roughness decreases at higher cutting speed during machining of Al/B₄C MMCs.
- From the experimental results, the surface roughness of the machined surface has lower with limiting criteria of 2 μm except few trials obtained by coated insert. This improvement is due to presence of multilayer coating on the carbide inserts i.e. Al₂O₃ for thermal barrier, TiN for diffusion wear and TiCN for wear resistant.
- The flank wear evolution is observed at trial 3, 5 and 7. From the experimental results, high cutting force is observed for above mentioned trial. This flank wear is due to higher cutting speed and depth of cut. Abrasion is found to be the dominant wear and no crater wear is observed due to lubricity provided by TiN coated layer and prevent the tool work interface temperature by Al₂O₃ and diffusion wear by TiCN at higher cutting speed thus delay the growth of wear and consequently surface roughness criteria is observed within the limit of 0.2 μm.
- The better machining performance i.e. lower cutting force and better surface roughness is observed due to presence of thermal coating barrier Al₂O₃ in between TiN and TiCN. Moreover, the TiN at top and bottom

layer protects the flank of tool tip by providing the lubricity at the interface.

- The developed regression model has highly significant. This helps to indicate the model is highly significant and also the experimental results and predicted values for the responses criteria are very close to each other. Taguchi and mathematical model holds goodness for the workpiece surface roughness and cutting force in dry turning operation so this can be applicable for other machining process
- The optimal parametric combination for multi-responses in dry machining of composites mixture is found to be cutting speed at level 2 (100m/min), feed rate at level 1 (0.103 mm/rev) and depth of cut at level 2 (0.6 mm). Based on results of analysis of variance for the grey relational grade value, the feed rate with 62% of contribution is the most significant machining parameter for the simultaneous optimization of surface roughness and cutting force on dry turning operation followed by the depth of cut with 12.6% and cutting speed of 7.28%.
- From this research, the potential and effectiveness of the multi layer coated carbide insert (TiN/Al₂O₃/TiCN/TiN) has been identified for dry machining of Al/B₄C metal matrix composites.

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