Assessment of Surface Roughness and Material Removal Rate on Machining of TIB2 Reinforced Aluminum 6063 Composites: A Taguchi's Approach

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Abstract- The utilization of TiB2 particles reinforced aluminum (Al6063) metal matrix composite materials in many different engineering fields has undergone a tremendous increase. Accordingly, the need of accurate machining of composites has increased enormously; an attempt has been made to assess the factors influencing surface roughness and material removal rate on machining the composite. The orthogonal array, the signal-to-noise ratio, and analysis of variance were employed to study the performance characteristics in turning operations of 5 and 10 wt. % TiB2 particles reinforced aluminum (Al6063) metal matrix composites. Taguchi method was used to find the optimal cutting factors for surface roughness (Ra) and material removal rate (MRR). Three cutting factors namely speed; feed and depth of cut were optimized with considerations of Ra and MRR. The experimental plan and analysis was based on the Taguchi L27 orthogonal array with three cutting factors using carbide tool (K20). The optimal parametric combination for K20 carbide insert was found to be feed, speed and depth of cut. The analysis of variance (ANOVA) result shows that feed the most significant process parameter on surface roughness followed by speed. The depth of cut was found to be insignificant from the study. For MRR result show that the speed and the feed are the most significant parameters followed by the composition of composite material.

***Index Terms*-** TiB2 reinforced 6063 aluminum composites, Taguchi Method, Analysis of variance, Surface Roughness, Material Removal Rate.

I. INTRODUCTION

Aluminium alloys are the most widely used non ferrous materials in engineering applications owing to their attractive properties such as high strength to weight ratio, good ductility, excellent corrosion resistance, availability and low cost [1]. However, their applications have often been restricted because conventional aluminium alloys are soft and notorious for their poor wear resistance. This problem is over by reinforcing hard ceramic particles in aluminium and its alloys to produce a discontinuous reinforced metal matrix composite which possesses nearly isotropic properties.

Aluminum based particulate reinforced metal matrix composites have emerged as an important class of high performance materials for use in aerospace, automobile, chemical and transportation industries because of their improved strength, high elastic modulus and increased wear resistance over conventional base alloys. Recently, In-situ techniques have been developed to fabricate aluminum-based metal matrix composites [3-4], which can lead to better adhesion at the interface and hence better mechanical properties. In-situ composites are multiphase materials where the reinforcing phase is synthesized within the matrix during composite fabrication. There are different routes to Synthesize Al–TiB2 composites, but in-situ approach is gaining importance due to simplicity of its fabrication. Among the reinforcements, TiB2 has emerged as a promising candidate for Al-based composites. This is due to the fact that TiB2 is stiff, hard and more importantly, does not react with aluminum to form reaction product at the interface of reinforcement and matrix. TiB2 is a refractory compound that exhibits outstanding features such as high melting point (2790°C), high hardness (86 HRA or 960 HV) and high modulus characteristics. Its resistance to plastic deformation even at high temperatures portrays it to be a good potential reinforcing candidate in an aluminum matrix. 5 and 10 wt. % TiB_2 particles reinforced aluminum (Al6063) metal matrix composites produced by using master alloys of Al-Ti & B by stir casting process to obtain the material for the experiment [5-7].

Surface roughness has become the most significant technical requirement and it is an index of product quality. In order to improve the tribological properties, fatigue strength, corrosion resistance and aesthetic appeal of the product, a reasonably good surface finish is desired. Nowadays, the manufacturing industries specially are focusing their attention on dimensional accuracy and surface finish. In order to obtain optimal cutting parameters to achieve the best possible surface finish, manufacturing industries have resorted to the use of handbook based information and operators' experience. This traditional practice leads to improper surface finish and decrease in the productivity due to sub-optimal use of machining capability. This causes high manufacturing cost and low product quality [8-11]. In addition to the surface finish quality, the material removal rate (MRR) is also an important characteristic in turning operation and high MRR is always desirable [8, 12].

Hence, there is a need to optimize the process parameters in a systematic way to achieve the output characteristics/responses by using experimental methods and stastical models. Dr. Taguchi employed design of experiments (DOE), which is one of the most important and efficient tools of total quality management (TQM) for designing high quality systems at reduced cost. Taguchi emphasizes on the fact that Quality provides robustness and immune to the uncontrollable factors in the manufacturing state. This approach helps to reduce the large number of experimental trials when the number of process parameters increases. [14-16]

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In the present investigation, optimization model based on Taguchi method and utility concept has been employed to determine the best combination of the machining parameters such as cutting speed, feed, and depth of cut to attain the minimum surface roughness and maximum MRR simultaneously. The predictive models obtained were used for performance measures.

II. Design of Experiments

Experimental design is a statistical technique that enables an investigator to conduct realistic experiments, analyze data efficiently, and draw meaningful conclusions from the analysis. The aim of scientific research is usually to show the statistical significance of an effect that a particular factor (input parameter) exerts on the dependent variable (output/response) of interest. Specifically, the goal of DOE is to identify the optimum settings for the different factors that affect the production process. The primary reason for using statistically designed experiments is to obtain maximum information from minimum amount of resources being employed. An experiment (also called run) may be defined as a test in which purposeful changes are made to the input variables of a process so that the possible reasons for the changes in the output/response could be identified. The experimental strategy frequently practiced by the industries is **one factor at-a time approach** in which the experiments are carried out by varying one input factor and keeping the other input factors constant. This approach fails to analyze the combined effect, when all the input factors vary together which simultaneously govern the experimental response. A well designed experiment is important because the results and conclusions that can be drawn from the experimental response depend to a large extent on the manner in which data were collected.

A. Factorial designs

This is an experimental strategy, in which all the factors of study are varied together, instead of one at a time. If the factorial experiment has 2 factors at 2 levels (values) each, all possible combinations of the two factors across their levels are used in the design. As the number of factors of interest increases the number of experiments increases rapidly. Though this method is efficient, it is not feasible from the point of view of time and resources, when the number of factors and their levels are relatively large.

B. Taguchi designs

A Taguchi design, or an Orthogonal Array (OA), is a method of designing experiments that usually requires only a fraction of the full factorial combinations. Taguchi designs provide a powerful and efficient method for designing processes that operate consistently and optimally over a variety of conditions. Taguchi techniques have been used widely in engineering and scientific community because they are easy to adopt and apply for users with limited knowledge in statistics [13, 14]. An orthogonal array provides a set of well balanced experiments in which factor levels are weighted equally across the entire design. Because of this, each factor can be evaluated independently of all the other factors, so the effect of one factor does not influence the estimation of another factor.

C. Analysis of variance Analysis of Variance (ANOVA)

ANOVA is a statistical decision making tool, used to analyze the experimental data, for detecting any differences in the response means of the factors being tested. ANOVA is also needed for estimating the error variance for the factor effects and variance of the prediction error. In general, the purpose of analysis of variance is to determine the relative magnitude of the effect of each factor and to identify the factors significantly affecting the response under consideration (objective function).

D. Main effects

The change in average response produced by a change in the level of a factor is called “Main Effect” of that factor. The main effects plot displays the response means for each factor level in the sorted order. The points (response means) in the plot are located with respect to a reference line drawn at the overall mean of the response data and connected by a line.

- When the line is horizontal (parallel to x-axis), then there is no main effect present. Each level of the factor affects the response in the same way, and the response mean is the same across all factor levels.
- When the line is not horizontal, then there is a main effect present. Different levels of the factor affect the response differently. The steeper the slope of the line, the greater the magnitude of the main effect.

E. Interaction effects

If the effect of one factor is different at different levels of another factor, the two factors are said to interact or to have interaction. The interaction between two factors A and B is termed as “first order or two factor” interaction, denoted by AB (A*B or AxB). Similarly, the interaction between three factors is referred as “second order or three factors” interaction. Minitab (Version 15) statistical software is used for designing experiments and for analyzing response data.

III. Experimental Work

A Material

The material used is of 0, 5 and 10wt % TiB_2 reinforced with Al6063 composite material of size Φ20 x 60 mm length shown in figure 1.

Figure 1: Composite Material 0, 5 & 10 wt% TiB_2 Reinforced with Al6063.

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B. Experimental Procedure

The experiments were carried with four factors at three levels each as shown in the table 1.

Table 1: Factors (process parameters) and Levels Used in the Experiments

Process Factors	Levels		
	1	2	3
A-Cutting peed (m/min)	37.69	75.39	113.07
B-Feed rate (mm/min)	0.05	0.10	0.15
C- Depth of cut (mm)	0.25	0.50	0.75
D- Material (Al6063 -wt% TiB_2)	0	5	10

The factorial design used is a standard L_{27} (3^{13}) orthogonal array. This orthogonal array is chosen due to its capability to check the interactions among factors. The turning trials were carried out on the CNC turning center (MITSUBISHI-EZ Motion NC E60) in dry machining condition as shown in figure2.

Figure 2.: CNC turning center. (MITSUBISHI-EZ Motion NC E60)

The insert used is of K_{20} type carbide tool (SANDVIK: DNMG 3215 TOOL: $K_5 - K_{20}$) shown in Fig. 3.

Figure 3: SANDVIK: DNMG 3215 Tool ($K_{15} - K_{35}$)

Table 2:. Factor settings, surface roughness data and MRR data

Exp No	Cutting Speed (m/min)	Feed (mm/ min)	Depth of cut (mm)	wt% TiB2	Material Removal Rate (mm^3/ min)	Surface Roughness (R_a) µm
1	37.69	0.05	0.25	0	0.40	0.152
2	37.69	0.05	0.50	5	0.73	0.276
3	37.69	0.05	0.75	10	1.90	0.099
4	37.69	0.10	0.25	5	1.47	0.282
5	37.69	0.10	0.50	10	1.73	0.719
6	37.69	0.10	0.75	0	0.57	0.590
7	37.69	0.15	0.25	10	1.70	0.325
8	37.69	0.15	0.50	0	1.87	0.724
9	37.69	0.15	0.75	5	1.95	1.066
10	75.39	0.05	0.25	5	0.60	0.339
11	75.39	0.05	0.50	10	0.90	0.553
12	75.39	0.05	0.75	0	1.00	0.793
13	75.39	0.10	0.25	10	1.10	0.367
14	75.39	0.10	0.50	0	0.87	1.653
15	75.39	0.10	0.75	5	1.20	1.616
16	75.39	0.15	0.25	0	1.73	0.925
17	75.39	0.15	0.50	5	2.32	2.678
18	75.39	0.15	0.75	10	1.57	1.396
19	113.07	0.05	0.25	10	0.63	0.504
20	113.07	0.05	0.50	0	0.60	0.717
21	113.07	0.05	0.75	5	0.87	0.727
22	113.07	0.10	0.25	0	0.67	1.037
23	113.07	0.10	0.50	5	1.67	2.397
24	113.07	0.10	0.75	10	0.83	1.925
25	113.07	0.15	0.25	5	1.50	1.525
26	113.07	0.15	0.50	10	1.37	2.865
27	113.07	0.15	0.75	0	0.70	3.032

The surface roughness (R_a) of the machined surface was measured using HANDSURF E-35A instrument and the MRR is calculated using the following equation [9].

$$MRR = \left\{ \frac{\text{[Intial weight of the work(gms) - Final Weight of the work(gms)]}}{\text{Density (gms/mm}^3\text{) x Machining time(min)}} \right\} (mm^3/min)$$

VI. EXPERIMENTAL RESULTS AND ANALYSIS

A. Analysis of variance of Surface Roughness (R_a) and MRR

The response data recorded in table 2, for surface roughness and MRR are subjected to ANOVA for finding the significant factors, at above 95% confidence levels and the result of ANOVA for these response parameters are presented in the tables 3, 4 and 5, 6 respectively.

B. Surface Roughness

Average S/N ration for every level of experiment and the different values of S/N ration between maximum and minimum are shown in Table 3 for surface roughness. The feed rate, TiB_2 reinforced Al6063 composite work material;

cutting speed and depth of cut are the factors with different values of 6.12, 3.61, 2.34 and 2.02 respectively. Based on the Taguchi prediction that the bigger different values of S/N ratio will give more effect or more significant. Increase in the feed rate will increase the surface roughness significantly.

Table 3. Average for S/N ration and main effect of Surface Roughness.

Process Factors	Designation	Levels 1	2	3	Max-Min	Rank
Cutting Speed (m/min)	A	-1.55	-1.32	0.79	2.344	3
Feed rate	B	2.24	-0.42	-3.89	6.124	1
Depth of cut	C	0.31	-1.71	-0.67	2.025	4
Wt% TiB2	D	1.65	-1.96	-1.76	3.612	2

The results of analysis of variance for surface roughness are shown in table 4. DF (degree of freedom), SS (sum of squares), MS (mean of squares), F (variance ratio), P (Significant factor) and percentage contribution of each level [14, 15].

Table 4 shows that the feed rate and the TiB_2 reinforced Al6063 work material have more influence on the surface roughness value. Significant factor (P) values for both are 0.024 and 0.158 respectively. In statistical analysis of taguchi method, the smallest P value gives more significant effect on responded surface roughness parameters. The significant values for the feed rate and the TiB_2 reinforced Al6063 composite work material and their contributions are 38.52% and 13.22% respectively. The speed and TiB_2 reinforced Al6063 work material interaction contributes about 11.20%, where as the contribution of the cutting speed is about 9.53% and the other interactions and depth of cut are insignificant. The most significant factor, which affects the surface roughness measured in turning the 5 and 10wt % TiB_2 reinforced with Al6063 composite material, is the feed rate, therefore the surface roughness can be controlled with a suitable feed rate Value. Previous researchers suggest the similar results. They claimed that the surface roughness strongly depends on the feed rate. [15-17].

Table 4. ANOVA Analysis of S/N Ration for Surface finish

Process Parameters	Desig nation	DF	SS	MS	F	P	SS (%)
Cutting Speed (m/min)	A	2	0.71	0.36	1.84	0.238	09.53
Feed rate (mm/min)	B	2	2.87	1.43	7.43	0.024	38.52
Depth of cut (mm)	C	2	0.29	0.15	0.76	0.509	03.89
wt%TiB2 material	D	2	0.98	0.49	2.55	0.158	13.22
Speed* Feed	A*B	4	0.41	0.10	0.53	0.722	05.50
Speed * DOC	A*C	4	0.19	0.05	0.25	0.900	02.68
Speed * %TiB2	A* D	4	0.84	0.21	1.08	0.443	11.20
Error		6	1.16	0.19			15.55
Total		26	7.45				100.0

R-Sq = 84.45%

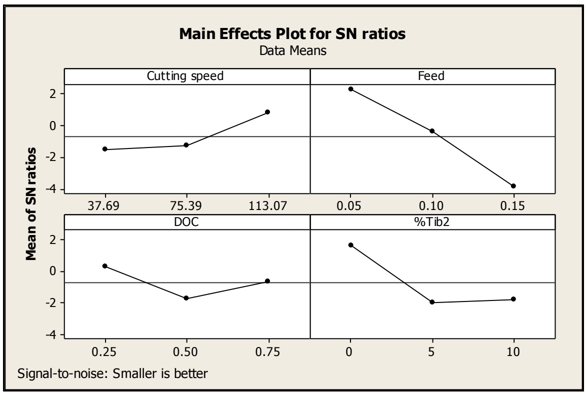

Figure 4. Main effect plots for SN rations of process factors on Surface Roughness

The signal to noise ratio are shown in Figure 4 for the process factors on surface roughness. The B1 (low level of feed) is at the maximum value with 2.24 of S/N ratio, decrease dramatically to B2 (-0.42) and then to B3 (-3.89). S/N ratio for B2 and B3 decreased, due to increase in the feed rate. The parameter D1 (low level of material composition) is at the maximum value at 1.65 and it decreased to a value of -1.76 as the feed increases. The cutting speed is at the minimum value of -1.55 and increased to 0.79.

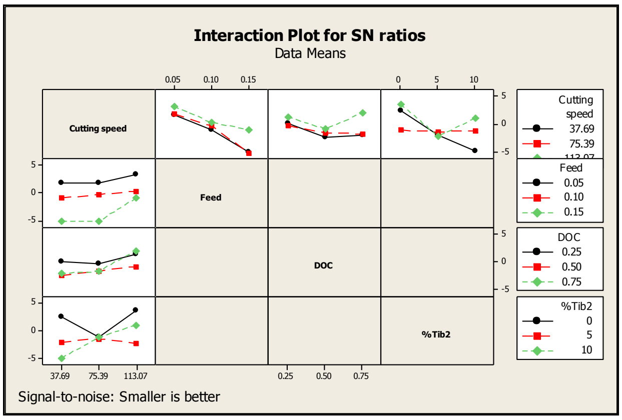

Figure 5. Interaction plot for SN rations of process factors on Surface Roughness

The interactions among the factors are shown in Figure 5 for surface roughness. The cutting speed and the type of work material contribute the most of about 11.32% and become significant. The other interactions are insignificant.

C. Material Removal Rate (MRR)

In machining operation, maximizing the material removal rate (MRR) is an important criterion. Experimental results of the material removal rate for turning 5 and 10 wt% TiB2 reinforced with Al6063 composites material with various turning parameters are shown in table 5, which also gives the S/N ratio for the material removal rate. The cutting speed and the feed are the most significant factor that influences the MRR with the value of 11.39 and 10.78 respectively.

Table 5. Average for S/N ration and main effect of MRR

Process Factors	**Designation**	**Levels** 1	2	3	**Max-Min**	**Rank**
Cutting Speed (m/min)	A	-8.66	-0.66	2.71	11.391	1
Feed rate (mm/min)	B	-8.42	-0.56	2.36	10.778	2
Depth of cut (mm)	C	-6.43	0.53	-0.72	6.960	3
Wt% TiB2 material	D	1.67	-1.09	-3.87	2.776	4

Table 6. Provides the cutting speed and feed rate values are significant with the factor (P) value for both are 0.001 & 0.002 respectively. The contribution of the cutting speed and feed rate are 32.28% and 31.85% respectively. The depth of cut contributes about 16.64% and the other factor and interactions are insignificant.

Table 6. ANOVA Analysis of S/N Ration for MRR

Process parameters	**Designation**	**DF**	**SS**	**MS**	**F**	**P**	**SS (%)**
Cutting Speed (m/min)	A	2	6.17	3.09	23.37	0.001	32.28
Feed rate (mm/min)	B	2	6.09	3.05	23.08	0.002	31.85
Depth of cut (mm)	C	2	3.19	1.59	12.07	0.008	16.64
Wt %TiB2 material	D	2	0.26	0.13	0.99	0.426	01.35
Speed* Feed	A*B	4	1.29	0.32	2.44	0.158	06.75
Speed * DOC	A*C	4	0.57	0.14	1.08	0.444	02.98
Speed * %TiB2	A*D	4	0.75	0.19	1.43	0.332	03.92
Error		6	0.79	0.13			04.13
Total		26	19.12				100.00

R-Sq = 95.86%

Figure 6 shows that the A1 (low cutting speed) is the minimum value with -8.68 of S/N ratio, and it increases dramatically to A2 (-0.66) and then to A3 (2.37). The main effect plot for the feed, and depth of cut have same trend lines but the TiB_2 reinforced Al6063 composite work material shows inverse trend as wt% of TiB_2 increases the MRR decreases.

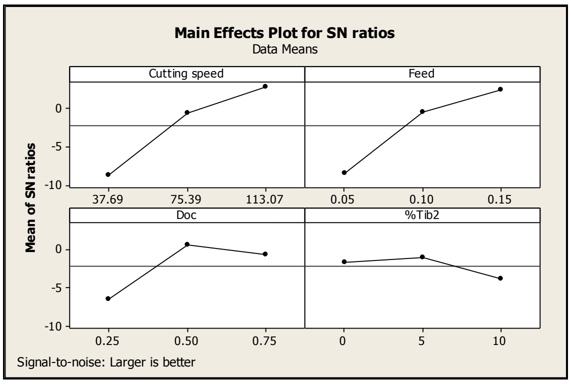

Figure 6. Main effect plots for SN rations of Process factors on MRR.

The interactions among the factors are shown in figure 7 for the MRR. The cutting speed and the feed contribute the most of about 6.75% and become less significant. The other interactions are insignificant.

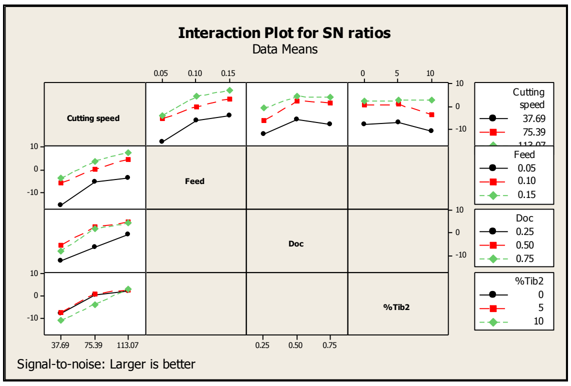

Figure 7. Interaction plot for SN rations of Process Factors on MRR

Table 7. Factors with optimum levels for Surface Roughness and MRR

Process parameters	**Optimum Level for Surface Finish**	**Optimum values for Surface Finish**	**Optimum Level for MRR**	**Optimum values for MRR**
Cutting Speed (m/min)	A3	113.07	A3	113.07
Feed rate (mm/min)	B1	0.05	B3	0.15
Depth of cut (mm)	C1	0.25	C3	0.75
wt%TiB2 + Al60603 material	D1	0%	D1	0%

IV. Conclusions

- Taguchi robust design method is suitable to optimize the surface roughness and the material removal rate is adopted in the present work.

- The significant factors in turning 5 and 10 wt. % TiB_2 particles reinforced aluminum (Al6063) metal matrix composites material on surface roughness were feed rate and the type of work material, with contribution 38.52% and 13.22% respectively.

- For MRR the cutting speed and the feed rate are most significant factors, with contribution of 32.28% and 31.85% respectively. The depth of cut is contributed about 16.64%.

- The optimal conditions for surface roughness and the MRR are shown in Table 7.

- The optimal condition of cutting parameters for lesser surface roughness for the Al6063/TiB_2 composite material are the cutting speed of 113.07m/min; feed rate of 0.05 mm/min and the depth of cut of 0.25mm.

- The optimal condition of cutting parameters for higher material removal rate for the Al6063//TiB_2 composite material are the cutting speed 113.07m/min, feed rate of 0.15 mm/min and the depth of Cut of 0.75mm.

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