Taguchi's Technique in Machining of Metal Matrix Composites

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This paper presents the study on Taguchi's optimization methodology, which is applied to optimize cutting parameters in turning of age hardened Al6061-15% vol. SiC 25 µm particle size metal matrix composites with Cubic boron nitride inserts (CBN) KB-90 grade using steam as cutting fluid. Analysis of variance (ANOVA) is used to study the effect of process parameters on the machining process. This procedure eliminates the need for repeated experiments, time and conserves the material by the conventional procedure. The turning parameters evaluated are speed, feed, depth of cut, nozzle diameter and steam pressure. A series of experiments are conducted using PSG A141 lathe (2.2 KW) to relate the cutting parameters on surface roughness, tool wear, cutting force, feed force, and thrust force. The measured results were collected and analyzed with the help of the commercial software package MINITAB15. As well, an orthogonal array, signal-to-noise ratio is employed to analyze the influence of these parameters. The method could be useful in predicting surface roughness, tool wear, cutting force, feed force and thrust force as a function of cutting parameters. From the analysis using Taguchi's method, results indicate that among the all-significant parameters, steam pressure is the most significant parameter.
Keywords*: metal matrix composites, design of experiments, steam, surface roughness, tool wear, cutting force, feed force, thrust force*

Introduction

Metal matrix composites (MMCs) derive their excellent mechanical properties from the combination of a hard reinforcement phase such as silicon carbide (SiC) and a ductile matrix material such as aluminum or magnesium. While current applications for this class of materials are primarily limited to aerospace and automotive applications, their development continues with resulting new products such as high voltage power transmission lines and heat sinks for electronic components (Evans et al, 2003).

In the 1990s, Podgorkv (1992) and Godelvski (1998) proposed a new and pollution-free green cutting technique with water vapor as coolant and lubricant during cutting process. Further fluid jet assisted machining as a highly effective method for cutting of conventional materials has been well explored by various researchers (Li; Seah, 2001) (Li, 1996a, 1996b) (Kaminski; Alvelid, 2000) (Hung; Yeo, 1997) (Weinert, 1993) (Wang; Rajurkar, 1997) (Mazurkiewicz et al., 1989) (Raviraj Shetty et al., 2006a, 2006b, 2006c, 2007a, 2007b) (Shenoy et al., 2006). Fluids such as air, water or steam mainly act as transportation carriers carrying the heat away from the cutting region, and the efficiency of such a cooling method largely depends on the jet pressure. Therefore, it is necessary to understand the relationship among the various controllable parameters and to identify the important parameters that influence the quality of turning. Moreover, it is necessary to optimize (Singh; Kumar, 2004, 2005) (Davim, 2001) the cutting parameters to obtain an extended tool life and a better productivity, which are influenced by surface roughness, tool wear, cutting force, feed force and thrust force. Design of experiment (DOE) is a statistical-based approach to analyze the influence of known process variables over unknown process variables. The present work deals with the aim of understanding the features of DOE for process optimization in turning of age hardened Al6061-15vol.% SiC 25µm particle size with Cubic boron nitride inserts (CBN) KB-90 grade using steam as cutting fluid.

Experimental Work

Material

Al–SiC MMC workpiece specimens having aluminum alloy 6061 as the matrix and containing 15% vol. of silicon carbide particles of 25 µm mean diameter in the form of cylindrical bars of 120 mm length and 40 mm diameter are manufactured at Vikram Sarbhai Space Centre (VSSC) Trivandrum by Stir casting process with pouring temperature 700-710°C, stirring rate 195 rpm, extrusion at 457°C, extrusion ratio 30:1, direct extrusion speed 6.1m/min to produce Ø40 mm cylindrical bars. The specimens were solutions treated for 2h at a temperature of 540^{o}C in a muffle furnace; Temperatures were accurate to within ±2^{o}C and quench delays in all cases were within 20 s. After solutionising, the samples were water quenched to room temperature, and subsequently aged for six different times to obtain samples with different Brinell hardness number (BHN), out of which one sample were selected, one with 94 BHN obtained at peakage condition, i.e. 2h at 220^{o}C respectively. Sample selected were kept in a refrigerator right after the heat treatments. Figure 1 shows the Photo micrographic image of Al-SiCp.

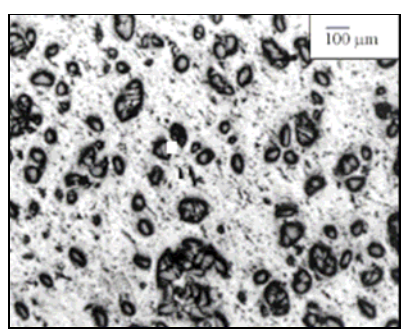

Figure 1. Photo micrographic image of Al-SiCp.

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Machining Test

The chemical composition of specimen is shown in Tab. 1. Turning method as a machining process was selected. The experimental study was carried out in PSG A141 lathe (2.2 KW). The selected cutting tool was Cubic Boron Nitride inserts KB-90 (ISO code), for machining of MMC materials. The ISO codes of cutting tool insert and tool holder were shown in Tab. 2, respectively. The level of variables used in the experiment were given in Tab. 3 with steam as cutting fluid and completed after 80s turning period. Surface condition of machined workpiece tool wear was observed using JEOL JSM-6380LA analytical scanning electron microscope. The cutting force and thrust force were measured by using an IEICOS Digital tool dynamometer respectively. Surface roughness was measured using Taylor/Hobson surtronoic 3+ surface roughness measuring instrument with cut-off length of 25.4 mm and averages of four readings were taken. Tool wear measurements were observed using Vision Plus Tool maker microscope METZ-1395 of range from 0-25 mm, least count – 10 µm and averages of four readings were taken. Figure 2 shows surface roughness and force measurement layout.

Table 1. Nominal chemical composition of Base metal (6061 Al alloy).

Element	Cu	Mg	Si	Cr	Al
Weight. percentage	0.25	1.0	0.6	0.25	Balance

Table 2. Details of cutting tool and tooling system used for experimentation.

Tool holder Specification	STGCR 2020 K-16 CTGPR 1212 F 11
Tool geometry Specification	Approach angle:91^0 Tool nose radius:0.4 mm Rake angle: 0^0 Clearance angle: 7^0
Tool insert CBN (KB-90) Specification	TPGN160304-LS TPGN 110304-LS

Table 3. Levels of variables used in the experiment.

Levels	Low	High
	-1	*1*
(A) Cutting speed *V* (m/min)	45	101
(B) Feed *f* (mm/rev)	0.11	0.25
(C) Depth of cut(mm)	0.5	1.0
(D) Nozzle diameter (mm)	2	4
(E) Steam Pressure *P* (bar)	4	10

Figure 2. Surface roughness and force measurement layout.

Steam Generator and Steam Feeding System

In steam lubrication, a steam jet was pumped through a steam hose and expelled through a nozzle on to the cutting zone. The test rig consisted of a saturated steam supplier source, a super heater, a servo valve and a pressure gauge for controlling the supply pressure, nozzle, and steam flow meter for steam flow rate measurements. The steam temperature at the exit of the nozzle was maintained at 110^{o}C, flow quantity of 36 l/h. Figure 3 shows the steam generator and steam feeding system.

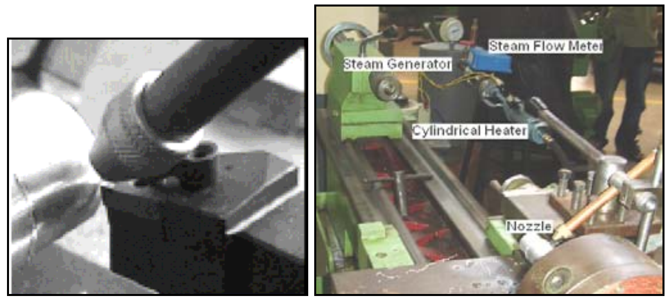


Figure 3. Steam generator and steam feeding system.

Taguchi's Method

Taguchi's techniques have been used widely in engineering design (Ross, 1996) (Phadke, 1989). The main trust of Taguchi's techniques is the use of parameter design, which is an engineering method for product or process design that focuses on determining the parameter (factor) settings producing the best levels of a quality characteristic (performance measure) with minimum variation. Taguchi designs provide a powerful and efficient method for designing processes that operate consistently and optimally over a variety of conditions. To determine the best design, it requires the use of a strategically designed experiment, which exposes the process to various levels of design parameters.

Experimental design methods were developed in the early years of 20th century and have been extensively studied by statisticians since then, but they were not easy to use by practitioners (Phadke, 1989). Taguchi's approach to design of experiments is easy to be adopted and applyed for users with limited knowledge of statistics; hence it has gained a wide popularity in the engineering and scientific community. There have been plenty of recent applications of Taguchi techniques to materials processing for process optimization; some of the previous works are listed in references (Yang; Tarng, 1998) (Su et al., 1999) (Nian et al., 1999) (Lin, 2002) (Davim, 2003) (Ghani et al., 2004). In particular, it is recommended analyzing metal cutting problems to find the optimal combination of parameters (Ghani et al., 2004). Further depending on the number of factors, interactions and their level, an orthogonal array is selected by the user. Taguchi has used Signal–Noise (S/N) ratio as the quality characteristic of choice. S/N ratio is used as measurable value instead of standard deviation due to the fact that, as the mean decreases, the standard deviation also deceases and vice versa. In other words, the standard deviation cannot be minimized first and the mean brought to the target. In practice, the target mean value may change during the process development. Two of the applications in which the concept of S/N ratio is useful are the improvement of quality through variability reduction and the improvement of measurement. The S/N ratio characteristics can be divided into three categories given by Eqs. (1) to (3), when the characteristic is continuous:

- nominal is the best characteristic

$$\frac{S}{N} = 10 \log \frac{\overline{y}}{s_y^2} \tag{1}$$

- smaller is the best characteristic

$$\frac{S}{N} = -10 \log \frac{1}{n}\left(\sum y^2\right) \tag{2}$$

- and larger the better characteristic

$$\frac{S}{N} = -\log \frac{1}{n}\left(\sum \frac{1}{y^2}\right) \tag{3}$$

where $\overline{y}$ is the average of observed data, s_y^2 the variation of y, n the number of observations, and y the observed data or each type of the characteristics, with the above S/N ratio transformation the smaller the S/N ratio, the better is the result when we consider tool wear, surface roughness, cutting force and trust force.

Two levels were specified for each of the factors as indicated in Tab. 3. The orthogonal array chosen was L_{32}, which has 32 rows corresponding to the number of parameter combinations (31 degrees of freedom), with 15 columns at two levels as shown in Tab. 4. The first column was assigned to the cutting speed (m/min), the second column to the feed rate (mm/rev), the third column to the depth of cut (mm), the fourth column to the nozzle diameter (mm), the fifth column to the steam pressure (bar), and the remaining columns to the interactions. One test was performed for each combination resulting in a total of 32 tests (no replications), which allows analysis of the variance of the results. Also a random order was determined for running the tests.

Experimental Results and Data Analysis

The plan of experiment is to find the important factors and combination of factors influencing the machining process to achieve the low surface roughness, tool wear, cutting force, feed force and thrust force values by using smaller the better characteristic. Table 5 illustrates the experimental results. The purpose of analysis of variance is to determine the parameters and combination of parameters significantly affecting the machining process. Taguchi recommends analyzing the S/N ratio using conceptual approach that involves graphing the effects and visually identifying the factors that appear to be significant.

The experimental results were analyzed with analysis of variance (ANOVA), which is used for identifying the factors significantly affecting the performance measures. The results of the ANOVA with the surface roughness, tool wear, cutting force, feed force and thrust force are shown in Tabs. 6-15. This analysis was carried out for a significance level of $\alpha = 0.05$, i.e. for a confidence level of 95%. Tables 6 -15 show the P-values, that is, the realized significance levels, associated with the F-tests for each source of variation. The sources with a P-value less than 0.05 are considered to have a statistically significant contribution to the performance measures.

Effect of Control Parameters on Surface Roughness

The calculated S/N ratio for five factors on the surface roughness in machining of MMCs for each level is shown in Fig. 4a. As shown in Tab. 6 and Figs. 4a-b steam pressure is a dominant parameter on the surface roughness followed by feed. The cutting speed had a lower effect on the surface roughness. Lower surface roughness is always preferred. The quality characteristic considered in the investigation is the smaller the better characteristics.

Table 4. Orthogonal L32 array for Taguchi.

Test No	Column No.														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	1	1	1	2	1	1	2	1	2	2
3	1	1	1	2	1	1	1	2	1	1	2	1	2	1	2
4	1	1	1	2	2	1	1	2	2	1	2	2	2	2	4
5	1	1	2	1	1	1	2	1	1	2	1	1	2	2	1
6	1	1	2	1	2	1	2	1	2	2	1	2	2	4	2
7	1	1	2	2	1	1	2	2	1	2	2	1	4	2	2
8	1	1	2	2	2	1	2	2	2	2	2	2	4	4	4
9	1	2	1	1	1	2	1	1	1	2	2	2	1	1	1
10	1	2	1	1	2	2	1	1	2	2	2	4	1	2	2
11	1	2	1	2	1	2	1	2	1	2	4	2	2	1	2
12	1	2	1	2	2	2	1	2	2	2	4	4	2	2	4
13	1	2	2	1	1	2	2	1	1	4	2	2	2	2	1
14	1	2	2	1	2	2	2	1	2	4	2	4	2	4	2
15	1	2	2	2	1	2	2	2	1	4	4	2	4	2	2
16	1	2	2	2	2	2	2	2	2	4	4	4	4	4	4
17	2	1	1	1	1	2	2	2	2	1	1	1	1	1	1
18	2	1	1	1	2	2	2	2	4	1	1	2	1	2	2
19	2	1	1	2	1	2	2	4	2	1	2	1	2	1	2
20	2	1	1	2	2	2	2	4	4	1	2	2	2	2	4
21	2	1	2	1	1	2	4	2	2	2	1	1	2	2	1
22	2	1	2	1	2	2	4	2	4	2	1	2	2	4	2
23	2	1	2	2	1	2	4	4	2	2	2	1	4	2	2
24	2	1	2	2	2	2	4	4	4	2	2	2	4	4	4
25	2	2	1	1	1	4	2	2	2	2	2	2	1	1	1
26	2	2	1	1	2	4	2	2	4	2	2	4	1	2	2
27	2	2	1	2	1	4	2	4	2	2	4	2	2	1	2
28	2	2	1	2	2	4	2	4	4	2	4	4	2	2	4
29	2	2	2	1	1	4	4	2	2	4	2	2	2	2	1
30	2	2	2	1	2	4	4	2	4	4	2	4	2	4	2
31	2	2	2	2	1	4	4	4	2	4	4	2	4	2	2
32	2	2	2	2	2	4	4	4	4	4	4	4	4	4	4

In the present investigation, when the steam pressure is set at 10 bar the surface roughness is minimized. Contrary to the steam pressure, feed had the maximum effect. The reason being that the increase in feed increases the heat generation and hence the tool wear, which results in higher surface roughness. The increase in feed also increases the chatter, and it produces incomplete machining of work piece, which leads to higher surface roughness. The results shown prove that the roughness of the machined surface is highly influenced by the feed. Based on the above discussion and also in the evident optimum conditions for the surface roughness, it can be established: cutting speed (a): 101 m/min, feed (b): 0.11 mm/rev, depth of cut (c): 1 mm, nozzle diameter (d): 2mm, steam pressure (e): 10 bar.

Table 7 shows the ranking of each cutting parameter using the response table for signal to noise ratios (smaller is better) obtained for different parameter levels.

Table 5. Experimental results for surface roughness, tool wear, cutting force, feed force and thrust force.

Test no.	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Nozzle Diameter (mm)	Steam Pressure (bar)	R_a (μm)	Tool wear (mm)	F_x Feed force (N)	F_y Cutting force (N)	F_z Thrust force (N)
1	45	0.11	0.5	2	4	3.94	1.010	85.148	159.670	52.635
2	45	0.11	0.5	2	10	2.90	0.500	33.095	100.345	17.685
3	45	0.11	0.5	4	4	5.00	1.550	76.211	224.172	62.298
4	45	0.11	0.5	4	10	2.32	0.900	40.149	72.899	19.810
5	45	0.11	1.0	2	4	3.66	1.552	101.124	197.397	54.783
6	45	0.11	1.0	2	10	2.50	0.660	38.014	115.700	23.450
7	45	0.11	1.0	4	4	4.82	1.452	135.097	232.149	74.114
8	45	0.11	1.0	4	10	2.44	0.830	69.982	97.707	42.863
9	45	0.25	0.5	2	4	4.71	1.255	100.945	207.748	87.707
10	45	0.25	0.5	2	10	2.84	0.550	45.540	106.331	16.897
11	45	0.25	0.5	4	4	4.66	1.455	114.177	262.835	54.384
12	45	0.25	0.5	4	10	2.98	0.890	50.903	112.223	35.642
13	45	0.25	1.0	2	4	4.46	1.155	121.414	301.818	65.216
14	45	0.25	1.0	2	10	2.70	0.650	51.527	144.085	38.734
15	45	0.25	1.0	4	4	5.64	1.255	126.148	253.941	90.342
16	45	0.25	1.0	4	10	2.44	0.851	88.095	128.096	83.529
17	101	0.11	0.5	2	4	3.96	1.333	128.368	192.448	76.243
18	101	0.11	0.5	2	10	2.34	0.756	78.028	175.132	23.875
19	101	0.11	0.5	4	4	3.68	1.345	135.671	183.369	93.597
20	101	0.11	0.5	4	10	2.72	0.985	69.430	108.481	39.444
21	101	0.11	1.0	2	4	4.60	1.456	111.685	258.940	81.328
22	101	0.11	1.0	2	10	2.54	0.855	67.015	191.721	33.953
23	101	0.11	1.0	4	4	4.18	1.459	140.167	214.169	89.041
24	101	0.11	1.0	4	10	2.52	0.875	120.036	128.432	37.379
25	101	0.25	0.5	2	4	4.54	1.285	139.995	199.670	88.217
26	101	0.25	0.5	2	10	2.10	0.755	75.836	150.345	20.094
27	101	0.25	0.5	4	4	3.90	1.525	120.632	254.172	89.817
28	101	0.25	0.5	4	10	2.22	0.995	74.214	102.899	48.760
29	101	0.25	1.0	2	4	3.84	1.655	105.407	197.397	72.635
30	101	0.25	1.0	2	10	2.21	0.765	49.826	135.700	17.685
31	101	0.25	1.0	4	4	3.30	1.554	110.075	159.670	102.298
32	101	0.25	1.0	4	10	2.22	0.995	80.128	100.345	49.810

On the examination of the percentage of contribution (P%) of the different factors for surface roughness, Tab. 6, it can be seen that the steam pressure has the highest contribution of about 80.22%; thus steam pressure is an important factor to be taken into consideration while machining MMCs followed by feed (b) (P = 10.00%) and cutting speed (a) (P = 4.90%). Interactions do not present a statistical significance or a percentage of physical significance of contribution to the surface roughness. Figure 5 shows the SEM images showing the surface roughness on Al-SiC at steam pressure 4 bar and 10 bar.

Effect of Control Parameter on Tool Wear

Studies on tool wear have found that tool wear is predominantly caused by abrasion of the hard reinforcement particles in the MMCs. From Figures 5a-b it is very much clear that tool wear is lesser under 10 bar steam pressure compared to 4 bar. This is because lubrication effect of the steam jet enables the formation of saw-toothed type chips and more gaps appear at the chip and tool interface. This increase in gaps at the interface contributes to the higher penetrating ability of the steam and thus explains how very low tool wear readings are observed compared to 4 bar.

The calculated S/N ratio for five factors on the tool wear in machining of MMCs for each level is shown in Fig. 6a-b. As shown in Tab. 8 and in Figs. 6a-b, steam pressure is a dominant parameter on the tool wear. Based on the above discussion and also evident from Table 5a-b, the optimum conditions for the surface roughness can be established at cutting speed (a): 45 m/min, feed (b): 0.11 mm/rev, depth of cut (c): 1 mm, nozzle diameter (d): 2 mm, steam pressure (e): 10 bar.

Table 9 shows the ranking of each cutting parameter using the response table for signal to noise ratios (smaller is better) obtained for different parameter levels.

On the examination of the percentage of contribution (P%) of the different factors for surface roughness, Tab. 8, it can be seen that steam pressure has the highest contribution of about 77.28%; thus steam pressure is an important factor to be taken into consideration while machining MMCs. Interactions dxe, cxd, axd present a statistical significance, however other interactions do not present a statistical significance nor a percentage of physical significance of contribution to the tool wear. Figure 7 shows the SEM picture of the flank wear during machining of MMCs.

Table 6. Analysis of Variance for S/N ratios for surface roughness.

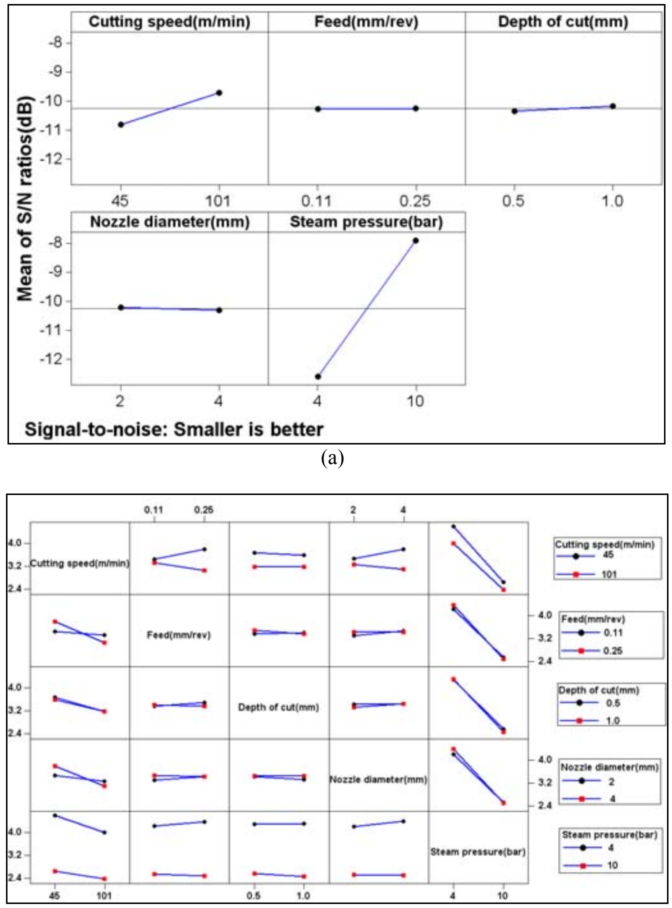
Source	DF	Seq SS	Adj SS	Adj MS	F	P	P(%)
a (m/min)	1	9.565	9.565	9.565	9.95	0.006	4.90
b (mm/rev)	1	0.002	0.002	0.002	30	0.963	10.00
c (mm)	1	0.246	0.246	0.246	0.26	0.620	0.13
d (mm)	1	0.066	0.066	0.066	0.07	0.797	0.03
e (bar)	1	176.027	176.027	176.027	150.11	0.000	80.22
a x b	1	5.802	5.802	5.802	6.04	0.056	2.98
a x c	1	0.244	0.244	0.244	0.25	0.621	0.12
a x d	1	1.178	1.178	1.178	1.23	0.285	0.61
a x e	1	0.111	0.111	0.111	0.12	0.738	0.06
b x c	1	0.525	0.525	0.525	0.55	0.470	0.27
b x d	1	0.230	0.230	0.230	0.24	0.632	0.12
b x e	1	0.617	0.617	0.617	0.64	0.435	0.32
c x d	1	0.024	0.024	0.024	0.02	0.877	0.01
c x e	1	0.160	0.160	0.160	0.17	0.689	0.08
d x e	1	0.311	0.311	0.311	0.32	0.578	0.16
Residual Error	16	15.381	15.381	0.961			
Total	31	210.489					

Table 7. Response table for S/N ratios - smaller is better (surface roughness).

Level	a (m/min)	b (mm/rev)	c (mm)	d (mm)	e (bar)
1	-10.803	-10.265	-10.344	-10.211	-12.602
2	-9.71	-10.248	-10.169	-10.302	-7.911
Delta	1.093	0.016	0.175	0.091	4.691
Rank	2	5	3	4	1

Table 8. Analysis of variance for S/N ratios for tool wear.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	P(%)
a (m/min)	1	12.293	12.293	12.293	20.79	0.000	4.93
b (mm/rev)	1	0.030	0.030	0.030	0.05	0.825	0.01
c (mm)	1	1.959	1.959	1.959	3.31	0.087	0.79
d (mm)	1	22.748	22.748	22.748	38.47	0.000	9.12
e (bar)	1	192.651	192.651	192.651	325.8	0.000	77.28
a x b	1	0.589	0.589	0.589	1	0.333	0.24
a x c	1	0.000	0.000	0.000	0	0.989	0.00
a x d	1	3.477	3.477	3.477	5.88	0.028	1.39
a x e	1	1.673	1.673	1.673	2.83	0.112	0.67
b x c	1	0.736	0.736	0.736	1.25	0.281	0.30
b x d	1	0.054	0.054	0.054	0.09	0.766	0.02
b xe	1	0.038	0.038	0.038	0.06	0.803	0.01
c x d	1	6.233	6.233	6.233	10.54	0.005	2.50
c x e	1	0.134	0.134	0.134	0.23	0.641	0.05
d x e	1	6.674	6.674	6.674	11.29	0.004	2.68
Residual Error	16	9.461	9.461	0.591			
Total	31	258.749					



(a)

(b)

Figure 4. Main effects plot and interaction plot for S/N ratio (surface roughness).

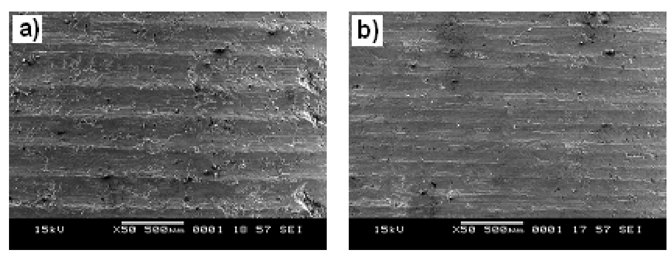
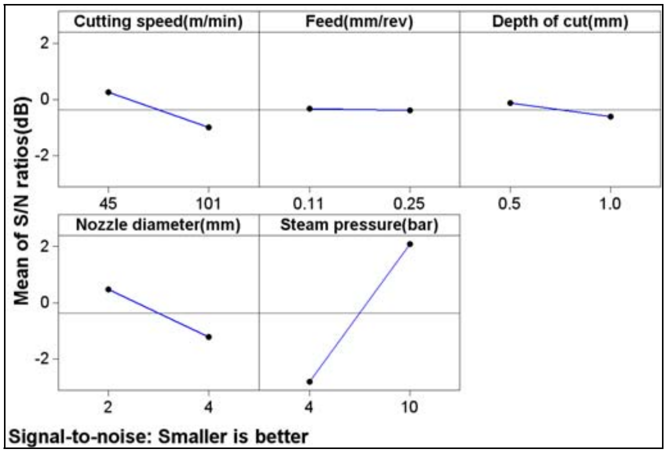


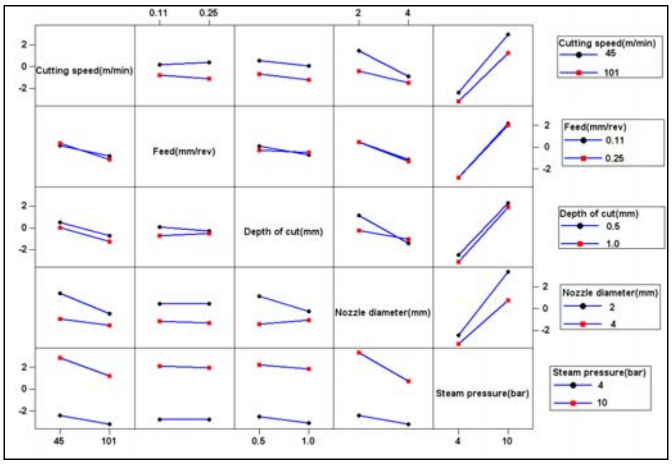
Figure 5. SEM images showing the surface roughness on Al-SiC at steam pressure (a) 4 bar, and (b)10 bar.

Table 9. Response table for S/N ratios - smaller is better (tool wear).

Level	a (m/min)	b (mm/rev)	c (mm)	d (mm)	e (bar)
1	0.2567	-0.3326	-0.1157	0.48	-2.8168
2	-0.983	-0.3938	-0.6106	-1.2063	2.0905
Delta	1.2396	0.0612	0.4949	1.6863	4.9073
Rank	3	5	4	2	1



(a)



(b)

Figure 6. Main effects plot and interaction plot for S/N ratio (tool wear).

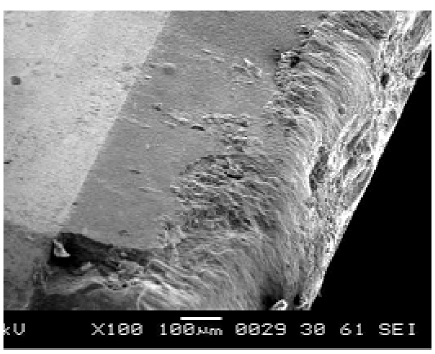


Figure 7. SEM picture of the flank wear during machining.

Effect of Control Parameter on Cutting Force, Feed Force and Thrust Force

In steam application, the cutting fluid is supplied at a high pressure and high velocity, resulting in the formation of minute capillaries, which penetrates in to the tool chip interface causing reduction in frictional contribution of the cutting force, thrust force and feed force. These minute capillaries exist at the tool chip interface and as the chip moves up it contacts mainly at the top of the asperities and draw in steam, which chemically reacts to produce a thin solid film of low shear strength. This film keeps the chip and the tool apart and it causes reduction in friction. At 10 bar, this high pressure steam is fragmented into tiny globules and the size of it is inversely proportional to the pressure of injection. The velocity varies as a function of the square root of the injection pressure. This high velocity facilitates better penetration of the steam to the underside of the chip, facilitating its passage to the tool chip interface and resulting in the reduction of friction. Such a condition is not possible in oil water emulsion, where no such fragmentation is taking place and the kinetic energy of the fluid jet is in no way comparable to that during steam injection. The calculated S/N ratio for five factors on the surface roughness in machining of MMCs for each level is shown in Figs. 8a-b, 9a-b, and 10a-b. As shown in Tabs. 10, 12, 14 and in Figs. 8a-b, 9a-b, 10a-b, steam pressure is a dominant parameter on the cutting force, thrust force and feed force. Based on the above discussion and also evident from the optimum conditions for the cutting force, thrust force and feed force, it can be established: cutting speed (a): 45 m/min, feed (b): 0.11 mm/rev, depth of cut (c): 0.5mm, nozzle diameter (d): 4 mm, steam pressure (e): 10 bar.

Tables 11, 13, 15 show the ranking of each cutting parameter using the response table for signal to noise ratios (smaller is better) obtained for different parameter levels.

Table 10. Analysis of variance for S/N ratios for cutting force.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	P (%)
a (m/min)	1	16.183	16.183	16.183	14.96	0.001	5.28
b (mm/rev)	1	5.863	5.863	5.863	5.42	0.033	1.91
c (mm)	1	4.270	4.270	4.270	3.95	0.064	1.39
d (mm)	1	9.988	9.988	9.988	9.23	0.008	3.26
e (bar)	1	205.794	205.794	205.794	190.28	0.000	67.20
a x b	1	18.889	18.889	18.889	17.46	0.001	6.17
a x c	1	8.364	8.364	8.364	7.73	0.013	2.73
a x d	1	0.010	0.010	0.010	0.01	0.925	0.00
a x e	1	9.302	9.302	9.302	8.6	0.010	3.04
b x c	1	0.100	0.100	0.100	0.09	0.765	0.03
b x d	1	2.916	2.916	2.916	2.7	0.120	0.95
b x e	1	2.633	2.633	2.633	2.43	0.138	0.86
c x d	1	3.770	3.770	3.770	3.49	0.080	1.23
c x e	1	4.375	4.375	4.375	4.05	0.061	1.43
d x e	1	13.810	13.810	13.810	12.77	0.003	4.51
Residual Error	16	17.304	17.304	1.082			
Total	31	323.570					

Table 11. Response table for S/N ratios - smaller is better (cutting force).

Level	a (m/min)	b (mm/rev)	c (mm)	d (mm)	e (bar)
1	-43.32	-43.61	-43.67	-43.48	-46.57
2	-44.75	-44.46	-44.4	-44.59	-41.5
Delta	1.42	0.86	0.73	1.12	5.07
Rank	2	4	5	3	1

On the examination of the percentage of contribution (P%) of the different factors (Tables 10, 12, 14), for cutting force, thrust force and feed force, it can be seen that steam pressure has the highest contribution of about 67.20%, 58.32 and 67.14; thus steam pressure is an important factor to be taken into consideration while machining MMCs. Interactions do not present a statistical significance, nor a percentage of physical significance of contribution to the surface roughness.

Table 12. Analysis of variance for S/N ratios for feed force.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	P (%)
a (m/min)	1	50.604	50.604	50.604	77.65	0.000	12.75
b (mm/rev)	1	1.003	1.003	1.003	1.54	0.233	0.25
c (mm)	1	7.899	7.899	7.899	12.12	0.003	1.99
d (mm)	1	21.537	21.537	21.537	33.05	0.000	5.43
e (bar)	1	231.384	231.384	231.384	355.04	0.000	58.32
a x b	1	19.922	19.922	19.922	30.57	0.000	5.02
a x c	1	20.651	20.651	20.651	31.69	0.000	5.21
a x d	1	0.740	0.740	0.740	1.14	0.302	0.19
a x e	1	11.177	11.177	11.177	17.15	0.001	2.82
b x c	1	4.330	4.330	4.330	6.64	0.020	1.09
b x d	1	1.183	1.183	1.183	1.82	0.197	0.30
b x e	1	0.010	0.010	0.010	0.02	0.904	0.00
c x d	1	15.735	15.735	15.735	24.14	0.000	3.96
c x e	1	1.280	1.280	1.280	1.96	0.180	0.32
d x e	1	9.319	9.319	9.319	14.3	0.002	2.35
Residual Error	16	10.428	10.428	0.652			
Total	31	407.203					

Table 13. Response table for S/N ratios - smaller is better (feed force).

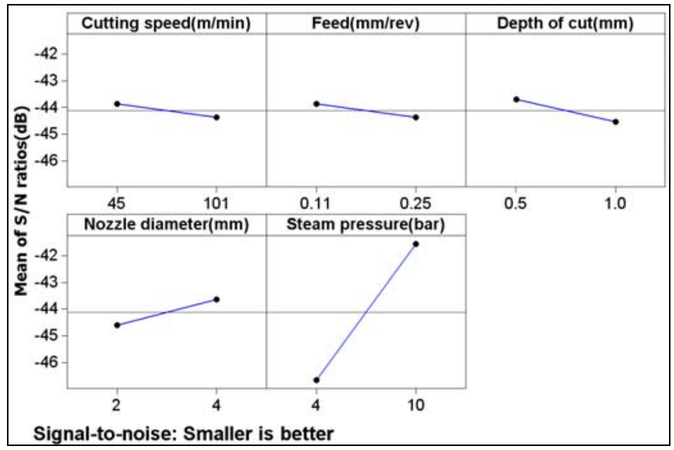
Level	a (m/min)	b (mm/rev)	c (mm)	d (mm)	e (bar)
1	-37.21	-38.29	-37.97	-37.64	-41.15
2	-39.72	-38.64	-38.96	-39.28	-35.77
Delta	2.52	0.35	0.99	1.64	5.38
Rank	2	5	4	3	1

Table 14. Analysis of variance for S/N ratios for thrust force.

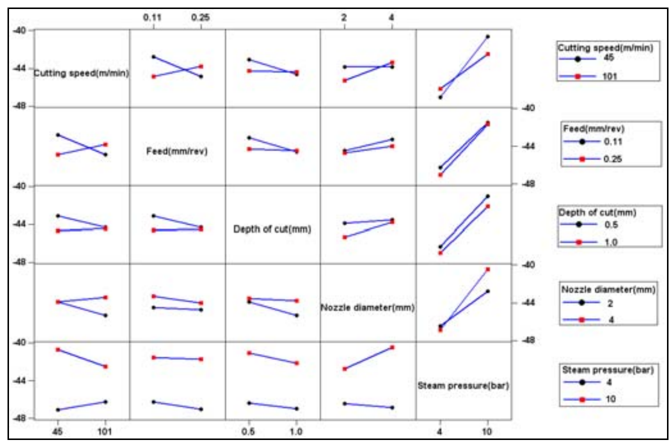
Source	DF	Seq SS	Adj SS	Adj MS	F	P	P (%)
a (m/min)	1	14.776	14.776	14.776	4.02	0.062	2.06
b (mm/rev)	1	12.071	12.071	12.071	3.29	0.089	1.68
c (mm)	1	25.715	25.715	25.715	7	0.018	3.58
d (mm)	1	77.313	77.313	77.313	21.05	0.000	10.78
e (bar)	1	481.481	481.481	481.481	131.11	0.000	67.14
a x b	1	16.593	16.593	16.593	4.52	0.049	2.31
a x c	1	21.470	21.470	21.470	5.85	0.028	3.00
a x d	1	0.924	0.924	0.924	0.25	0.623	0.13
a x e	1	6.718	6.718	6.718	1.83	0.195	0.94
b x c	1	0.047	0.047	0.047	0.01	0.911	0.01
b x d	1	5.767	5.767	5.767	1.57	0.228	0.80
b x e	1	0.608	0.608	0.608	0.17	0.690	0.09
c x d	1	4.637	4.637	4.637	1.26	0.278	0.65
c x e	1	15.353	15.353	15.353	4.18	0.058	2.14
d x e	1	33.628	33.628	33.628	9.16	0.008	4.69
Residual Error	16	58.759	58.759	3.672			
Total	31	775.860					

Table 15. Response table for S/N ratios - smaller is better (thrust force).

Level	a (m/min)	b (mm/rev)	c (mm)	d (mm)	e (bar)
1	-33.01	-33.08	-32.79	-32.14	-37.57
2	-34.37	-34.31	-34.59	-35.25	-29.81
Delta	1.36	1.23	1.79	3.11	7.76
Rank	4	5	3	2	1



(a)



(b)

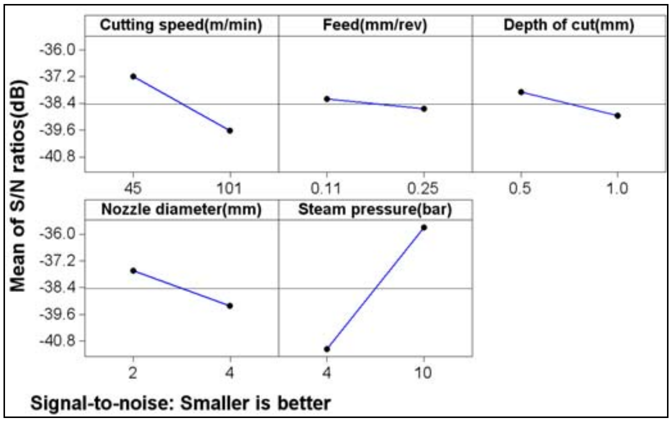
Figure 8. Main effects plot and interaction plot for S/N ratio (cutting force).

Conclusions

At the end of this work we thought of establishing a few valid conclusions for turning age hardened Al6061-15% vol. SiC 25 µm particle size with Cubic Boron Nitride inserts (CBN) KB-90 grade, using steam as cutting fluid and considering the methodology used.

The steam pressure is the most important parameter and has the highest physical as well statistical influence on surface roughness, tool wear, cutting force, feed force and thrust force (80.22%, 77.28%, 67.20%, 58.32% and 67.14% respectively)

The interaction steam pressure/nozzle diameter is the physical significance to the interactions analyzed in the tool wear, cutting force, feed force and thrust force required to perform the machining operation. The rest of interactions have no physical significance on influence of tool wear, cutting force, feed force and thrust force.



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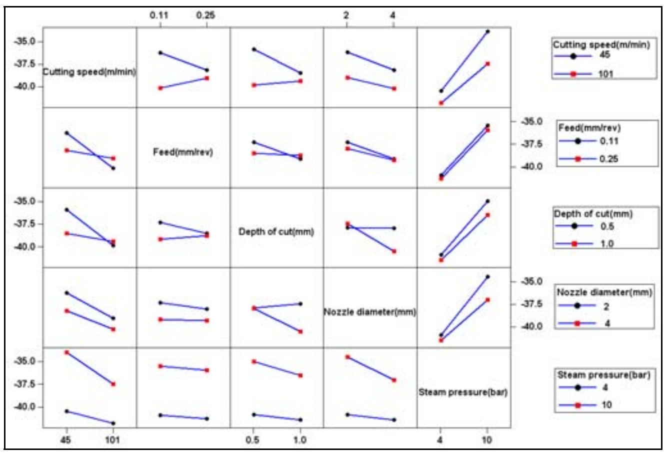
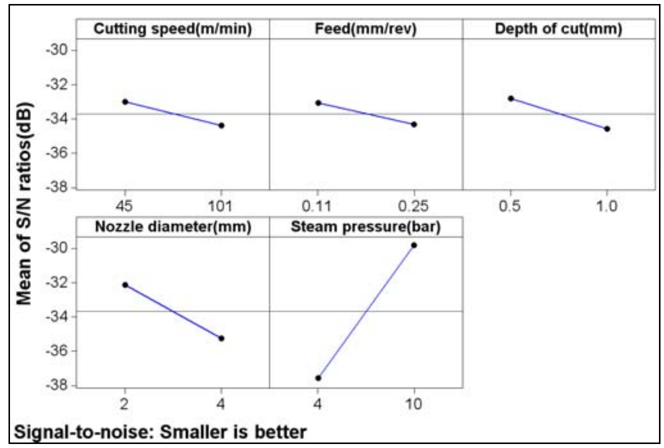
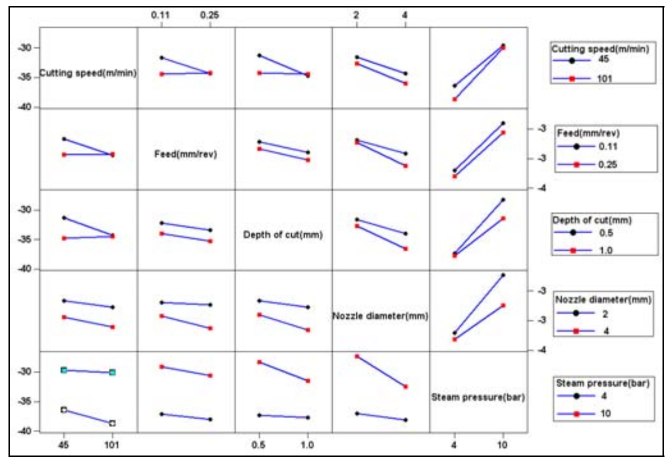


(b)

Figure 9. Main effects plot and interaction plot for S/N ratio (feed force).



(a)



(b)

Figure 10. Main effects plot and interaction plot for S/N ratio (thrust force).

The interaction cutting speed/feed is the physical significance to the interactions analyzed in the surface roughness required to perform the machining operation.

The ranking of each cutting parameter using the response table for signal to noise ratios (smaller is better) obtained for different parameter levels shows steam pressure as the dominant factor during machining.

The influence of operating parameters in steam application was evaluated and it was observed that the cutting performance mainly depends on fluid application parameters such as steam pressure and nozzle diameter. It is clearly seen from the results that by carefully choosing these parameters it is possible to produce high quality components under steam application.

The results of the study show that with a proper selection of machining parameters, it is possible to obtain a better performance under steam lubrication conditions in turning of MMCs.

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