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Research Article

Analysis for Optimization of Process parameters during Machining of Metal Matrix

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Abstract

In this thesis an attempt is made to study on process parameter optimization considering Taguchi orthogonal experimental design. Taguchi S/N ratio analysis method is used for single objective. The process parameters considered for optimization are the cutting speed of the tool in m/min, feed rate in mm/rev and the depth of cut in mm on turning machinery. The responses are the surface roughness and energy consumption in terms of power consumed for the machining process. The optimum levels of the process parameter need to be obtained. To validate the optimum predicted levels of the parameter, confirmation run was performed by setting the parameters at predicted optimum levels.

Keywords: *Surface roughness, cutting speed, feed rate, energy consumption.*

1. Introduction

A Metal Matrix Composite (MMC) is a composite material in which one constituent is a metal or alloy forming at least one percolating network, while the other constituent is embedded in this metal matrix and usually serves as reinforcement. The reinforcement in MMC could be particulate, fibers or whiskers with volume fraction ranging from a few percent to 40%. Compared to other materials, MMCs generally have much higher strength, stiffness and wear resistance as well as lower weight and thermal coefficient of expansion. In some cases they have lower lifecycle costs than other conventional materials.

MMCs have been available for quite some time but have only been recognized by industries in the 2nd half of the twentieth century. Increased interest in utilizing MMCs has motivated researchers to develop different types of MMCs. Over the last three decades, researchers on MMCs have provided not only new types of MMCs but also characterized them in terms of physical, thermo-mechanical, tribological and machining properties. Most of these studies were based on aluminium matrix composite materials (Surappa *et al* 2003). These studies focused on the machinability, specifically the tool life and the optimization of cutting tool performance.

MMCs are a potential substitute to conventional metals, alloys, and polymers in various applications due to their superior properties over the unreinforced alloys. Moreover, by utilising near-net shape forming and selective reinforcement techniques MMCs can offer economically viable solutions for a wide variety of commercial applications.

However, the final conversion of these composites in to engineering products is always associated with machining, either by turning or by milling. A continuing problem with MMCs is that they are difficult to machine, due to the high hardness and abrasive nature of the reinforcing particles. The particles used in the MMCs are harder than most of the cutting tool materials. Many researchers reported diamond is the most preferred tool material for machining MMCs (Chadwick *et al* 1990; Andrewes *et al* 2000; Paulo Davim 2003).

During the machining of MMC, the reinforcement particles are fractured and pulled out of the matrix which lead to the deterioration of the product surface quality, rapid tool wear, and increased machining costs. Moreover, premature failure of the cutting tool leads to recurrent tool changes which increases production time and cost (Looney *et al* 1992). However the machinability of these materials can be improved by appropriate selection reinforcing phase, its volume fraction, size, and morphology as well as the composition and hardness of the matrix material (Barnes *et al* 1995).

2. Manufacturing methods of MMC

There are different processes for manufacturing MMC which can be divided into two categories based on the operating state of matrix metal

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- Solid state processes
- Liquid state processes

Powder metallurgical processes, diffusion bonding, and vapour deposition are the techniques that come under the solid state technique.

3. Material chosen for the present work

In this research work, the silicon carbide particulate reinforced aluminium metal matrix composite (Al-SiC_p MMC) is taken for investigation. Although manufacturing of continuous fibre reinforced Al-matrix composites is rather complicated and expensive they are utilized in a few applications, especially in the aerospace industry. The whisker and short fibre reinforced MMCs are still in developmental stages for providing better properties than particulate reinforced MMCs at a fraction of the cost of continuous fibre MMCs. Among modern composite materials, particle reinforced MMCs are finding increased application owing to their very favorable properties, including high mechanical properties and good wear resistance. The inclusions of silicon carbide (SiC) particles in aluminium produce a combination of features which are not obtainable from the individual constituents. The hardness of these particles is about 2700 HV.

Unlike composites with continuous fibre reinforcement, the properties of particle reinforced composites are often isotropic. In addition, products can be fabricated from these materials using the techniques applied to conventional wrought alloys (Ling *et al* 1995). Silicon carbide (SiC_p) reinforced aluminium based MMCs are among the most common MMC and commercially available ones due to their properties such as low weight, heat-resistant, wear resistant and low cost. (Paulo Davim *et al* 2001a, Tamer ozban *et al* 2008)

The composite material under consideration, which is cast A356 aluminum alloy reinforced with 10% and 15% volume fraction of SiC particulates, is cited as Al-SiC_p (10p) and Al-SiC_p (15p). These metal matrix composites (MMCs) using A356 aluminum as the matrix material with SiC particles reinforced in it (A356/SiC_p), have found vast applications in automotive, aerospace, Electronics, Medical, Recreation and other allied fields, which have aggressive environments.

4. Objective of the present work

The cutting speed of the tool, feed rate and the depth of cut are the significant parameters which have effect on the surface quality and power consumed. The surface quality of the machined part and the input power consumed are the responses considered for optimization. In order to achieve the above mentioned primary objective, the following sub-objectives are formed.

1) To optimize the process parameters of machining process for turning Al-SiC_p (10P) and Al-SiC_p (15P) MMCs by single objective considerations,
2) To evaluate the surface roughness and power consumption of turning Al-SiC_p MMCs,
3) To investigate the effect of process parameters on surface roughness and power consumed of the machined work piece
4) To evaluate the process parameter optimization techniques like Taguchi, Desirability Function.

5. Experimental Procedure

In the Al-SiC_p MMC, the A356 aluminum matrix was experimentally found to contain 7.98% Si and 0.64% Mg apart from traces of other elements. Samples of the material Al-SiC_p MMC in the form of cylindrical rods of 50 mm diameter and 300 mm length were fabricated using stir cast method (see figure 3.4). The experimental work was carried out on a medium duty CNC lathe. The average temperature of the environment was maintained at 25±3 C during machining. The machining tests were conducted under dry cutting process. The experimental set up for machining is shown in Figure 3.5. Each of the experiment was repeated thrice and average value of the responses was measured. Power consumption was measured with a set of watt meters as three-phase supply was used and their readings were added after multiplying by suitable multiplying factor to get power consumption in kilowatts (kW).

Fig.1 Al-SiC_p composite samples used as work pieces (50 mm dia. and 300 mm long)

Fig.2 Photograph of Experimental setup

The machined surface was measured at three different positions and the average surface roughness (R_a) value in microns was taken using a Mitutoyo surf test (Make-Japan –Model SJ-301) measuring instrument with the cutoff length 2.5 mm

Fig.3 Photographic view of stylus during surface roughness measurement

Fig.4 Photograph of tool maker's microscope

6. Optimization of process parameters of turning Al-SiC$_p$ (10p) mmc using taguchi method

The following parameters were identified as potentially important in affecting the quality features of the turned parts under study.

- Cutting speed;
- Feed rate
- Depth of cut
- Work material – Al-SiC(10P) and Al-SiC(15P) MMCs; and Environment – dry

Table 1 Process parameters values and their levels

Symbol	Process parameters	Unit	Level 1	Level 2	Level 3
A	Cutting speed	m/min	75	120	180
B	Feed rate	mm/rev	0.1	0.2	0.3
C	Depth of cut	Mm	0.3	0.6	0.9

The experiments for turning operations were conducted according to the Taguchi's L9 orthogonal array (OA), which has 9 rows corresponding to the number of tests with 4 columns at three levels. The first column was assigned to the cutting speed (A), the second column to feed rate (B) and third column to the depth of cut (C). It considers three process parameters to be varied in three discrete levels. Each experimental run were replicated thrice and corresponding response values (results) for surface roughness (Ra) and power consumed (Pc) are listed. The surface roughness (Ra) measurements, in the transverse direction, on the work pieces have been repeated three times and average of three measurements values has been recorded for each replication. The power consumed (Pc) by main spindle was measured using digital watt meter.

6.1 Experimental procedure

The experiments for turning operations were conducted according to the Taguchi's L9 orthogonal array (OA), which has 9 rows corresponding to the number of tests with 4 columns at three levels. The first column was assigned to the cutting speed (A), the second column to feed rate (B) and third column to the depth of cut (C). It considers three process parameters to be varied in three discrete levels.. The surface roughness (Ra) measurements, in the transverse direction, on the work pieces have been repeated three times and average of three measurements values has been recorded for each replication. The power consumed (Pc) by main spindle was measured using digital watt meter.

Table 2 Experimental results using L9 OA for Al-SiC_P (10P) MMC

Exp. Run	Process parameters			Surface roughness in microns			Power consumption in kilo Watts		
	A	B	C	Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3
1	1	1	1	2.65	2.72	2.55	0.38	0.42	0.46
2	1	2	2	3.65	3.76	3.24	0.51	0.47	0.52
3	1	3	3	6.74	6.03	6.25	0.8	0.71	0.74
4	2	1	2	2.13	2.58	2.52	0.53	0.47	0.5
5	2	2	3	4.05	3.67	3.8	1.06	1.12	1.06
6	2	3	1	5.89	6.57	6.5	0.79	0.87	0.92
7	3	1	3	2.4	2.52	2.34	0.86	0.84	0.94
8	3	2	1	3.82	4.02	3.86	1.36	1.42	1.42
9	3	3	2	4.05	4.35	4.32	1.27	1.08	1.22

Table 3 Mean value and S/N ratio for Ra and Pc

Exp. Run	Process parameters			Mean value		S/N ratio	
	A	B	C	Ra (μm)	Pc (kW)	Ra (dB)	Pc (dB)
1	1	1	1	2.64	0.42	-8.435	7.509
2	1	2	2	3.55	0.5	-11.022	6.013
3	1	3	3	6.34	0.75	-16.051	2.488
4	2	1	2	2.41	0.5	-7.67	6.01
5	2	2	3	3.84	1.08	-11.694	-0.671
6	2	3	1	6.32	0.86	-16.024	1.293
7	3	1	3	2.42	0.88	-7.68	1.1
8	3	2	1	3.9	1.4	-11.823	-2.924
9	3	3	2	4.24	1.19	-12.552	-1.531

Since the experimental design is orthogonal, it is then possible to separate out the effect of each cutting parameter on the performance measures (Mean and S/N ratio) at different levels (Lin *et al* 2002). For example, the average S/N ratio for the cutting speed at levels 1, 2 and 3 can be calculated by averaging the S/N ratios for the experiments 1 to 3, 4 to 6, and 7 to 9, respectively. For example, the average S/N ratio for cutting speed at level 1 is calculated as the average of S/N ratios such as -8.435, -11.022 and -16.051 thus give the value of -11.836. Similarly average S/N ratio for cutting speed at level 2 is -11.796 (average of -7.670, -11.694 and -16.024), for cutting speed at level 3 is -10.685 (average of -7.680, -11.823 and -12.552). The average S/N ratio for each level of the other cutting parameters can be computed in the similar manner.

Similarly the main effects for the average mean value for each level of the cutting parameters can be computed. For example, the average mean value for cutting speed at level 1 is calculated as the average of 2.64, 3.55 and 6.34 thus give the value of 4.177. Similarly average mean value for cutting speed at level 2 is 4.190 (average of 2.41, 3.84 and 6.32), for cutting speed at level 3 is 3.520 (average of 2.42, 3.90 and 4.24). The main effects for both mean and S/N ratio values of all levels of the cutting parameters are calculated and listed for surface roughness and power consumption. Irrespective of the objective function whether maximization or minimization, the larger S/N ratio corresponds to the better quality characteristics. Therefore, the optimal level of the process parameters is the level with the highest average S/N ratio. Based on both mean and S/N ratio values, the optimal level setting is A3B1C2. i.e., the cutting speed is to set at 180 m/min, the feed rate has to be set at 0.1mm/rev and the depth of cut is to be 0.6mm based on the experimental results for the objective of minimum surface roughness.

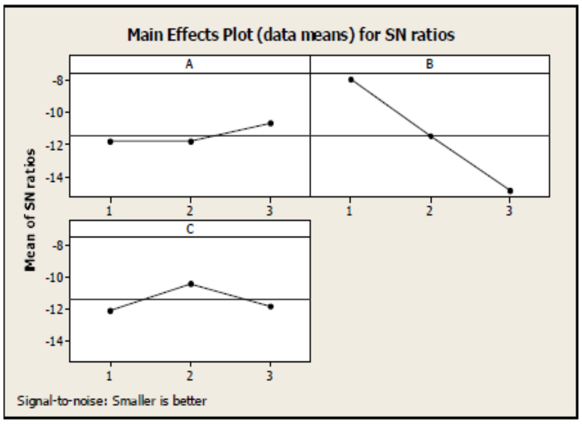

Fig.5 Main effects plot for surface roughness S/N ratio

The main effects, average mean and S/N ratio values of all levels of the cutting parameters are calculated. Based on mean and S/N ratio values for power consumption, the optimal level setting is A1B1C2. i.e., the cutting speed is to set at 75 m/min, the feed rate has to be set at 0.1mm/rev and the depth of cut is to be 0.6mm based on the experimental results for the objective of minimum power consumption. It was observed that the S/N ratio values increases with the decrease in cutting speed. The maximum S/N ratio is found when the cutting speed at the lowest level, i.e. 75 m/min. The S/N ratio decreases with the increase in the level of feed rate. The maximum value of S/N ratio is observed for the depth of cut at level 2.

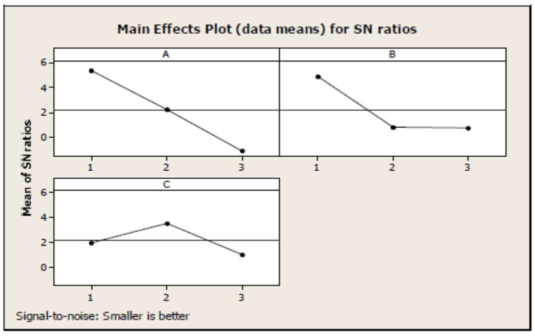

Fig.6 Main effects plot for power consumption S/N ratio

6.2 Analysis Of Variance (ANOVA)

The purpose of ANOVA is to find the significant factor statistically. It gives a clear picture of how far the process parameter affects the response and the level of significance of the factor considered. The F- test is being carried out for 95% confidence level to study the significances of the process parameter. The high F value indicates that the factor is highly significant in affecting the response of the process.

Table 4 ANOVA for surface roughness S/N ratio

Source	DoF	SS	MS	F	%P
A	2	2.5193	1.2597	1.7684	3.1
B	2	72.512	36.256	50.8985	89.11
C	2	4.9167	2.4584	3.4512	6.04
Residual Error	2	1.4246	0.7123		1.75
Total	8	81.372			100

Table 5 ANOVA for power consumption S/N ratio

Source	DoF	SS	MS	F	%P
A	2	62.6	31.3	31.8916	57.99
B	2	33.635	16.817	17.1353	31.16
C	2	9.7477	4.8738	4.96595	9.03
Residual Error	2	1.9629	0.9815		1.82
Total	8	107.95			100

In the present investigation, for the material Al-SiC$_p$ (10P) the feed rate (89.11%) is a highly significant factor and plays a major role in affecting the surface roughness of the machined surface. The cutting speed (57.99%) is major influencing factor for the response of power consumption followed by feed rate (31.16%). The effect of depth of cut does not make any impact in the responses.

7. Optimization of process parameters of turning Al-SiC$_p$ (15p) MMC using taguchi method

7.1 Process parameters and their levels

Table 6 Process parameters and their levels

Symbol	Process parameters	Unit	Level	Level	Level
	parameter		1	2	3
A	Cutting Speed	m/min	75	120	180
B	Feed rate	mm/rev	0.1	0.2	0.3
C	Depth of cut	mm	0.3	0.6	0.9

The experiments for Al-SiC$_p$ (15P) MMC turning operations were conducted according to the Taguchi's L_9 orthogonal array (OA), which has 9 rows corresponding to the number of tests with 4 columns at three levels. The first column was assigned to the cutting speed (A), the second column to feed rate (B) and third column to the depth of cut (C). It considers three process parameters to be varied in three discrete levels. Each experimental run were replicated thrice and corresponding response values (results) for surface roughness (Ra) and power consumed (Pc). The surface roughness (Ra) measurements, in the transverse direction, on the work pieces have been repeated three times and average of three measurements values has been recorded for each replication. The power consumed (Pc) by main spindle was measured using digital watt meter.

6.2 Experimental results

The experiments for Al-SiC$_p$ (15P) MMC turning operations were conducted according to the Taguchi's L_9 orthogonal array (OA), which has 9 rows corresponding to the number of tests with 4 columns at three levels. The first column was assigned to the cutting speed (A), the second column to feed rate (B) and third column to the depth of cut (C). It considers three process parameters to be varied in three discrete levels. Each experimental run were replicated thrice and corresponding response values (results) for surface roughness (Ra) and power consumed (Pc). The surface roughness (Ra) measurements, in the transverse direction, on the work pieces have been repeated three times and average of three measurements values has been recorded for each replication. The power consumed (Pc) by main spindle was measured using digital watt meter.

Table 7 Experimental results using L9 OA for Al-SiC_p (15P) MMC

Exp. Run	Parameters			Surface roughness in microns			Power consumption in		
	A	B	C	Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3
1	1	1	1	2.46	2.54	2.47	0.45	0.49	0.5
2	1	2	2	4.07	4.12	4.11	0.5	0.53	0.53
3	1	3	3	6.01	6.04	6.1	0.84	0.79	0.83
4	2	1	2	2.5	2.46	2.54	0.57	0.57	0.54
5	2	2	3	3.96	3.8	3.82	1.05	1.14	1.17
6	2	3	1	6.33	6.42	6.42	0.97	0.9	0.95
7	3	1	3	2.31	2.37	2.22	1.18	1.2	1.25
8	3	2	1	3.51	3.28	3.44	1.48	1.45	1.45
9	3	3	2	5.26	5.21	5.34	1.35	1.32	1.35

Table 8 Mean and S/N ratio values for Ra and Pc

Exp. Run	Parameters			Mean value of response(s)		S/N ratio	
run	A	B	C	Ra (µm)	Pc	Ra (dB)	Pc (dB)
					(kW)		
1	1	1	1	2.49	0.48	-7.925	6.366
2	1	2	2	4.1	0.52	-12.256	5.677
3	1	3	3	6.05	0.82	-15.635	1.721
4	2	1	2	2.5	0.56	-7.96	5.033
5	2	2	3	3.86	1.12	-11.733	-0.993
6	2	3	1	6.39	0.94	-16.11	0.533
7	3	1	3	2.3	1.21	-7.238	-1.658
8	3	2	1	3.41	1.46	-10.659	-3.287
9	3	3	2	5.27	1.34	-14.437	-2.543

Table 9 Main effects (Response) table for surface roughness

Process parameters	Level	Average Mean			Average S/N ratio		
		A	B	C	A	B	C
Average Value	1	4.213	2.430*	4.097	-11.939	-7.707*	-11.565
	2	4.25	3.79	3.957*	-11.934	-11.549	-11.551*
	3	3.660*	5.903	4.07	-10.778*	-15.394	-11.585
Delta (Max-Min)		0.59	3.473	0.14	1.161	7.687	0.034
Rank		2	1	3	2	1	3

Table 10 Main effects (Response) table for power consumption

Process parameters	Level	Average Mean			Average S/N ratio		
		A	B	C	A	B	C
Average Value	1	0.600*	0.743*	0.973	4.588*	3.247*	1.204
	2	0.873	1.033	0.890*	1.524	0.465	2.723*
	3	1.337	1.033	0.947	-2.496	-0.096	-0.31
Delta (Max-Min)		0.7367	0.29	0.083	7.084	3.343	3.033
Rank		1	2	3	1	2	3

Taguchi Signal-to-Noise (S/N) ratio is used as the performance index for the evaluation of responses. Smaller-the-better quality characteristics are used for both the responses of surface roughness and power consumed. The surface roughness (Ra) and power consumed (Pc) of the turning process is analyzed to study the effects of the process parameters. The experimental data are converted into mean and S/N ratio. For example the mean value of Ra for the first experimental run is calculated as the average of three replication results such as 2.46, 2.54 and 2.47 thus gives the mean value of 2.49. Similarly the mean values for Ra and Pc is calculated for all the experimental runs. The S/N ratio for each experimental run is calculated. For example the S/N ratio for Ra in first experimental run was calculated as $(-10 \log_{10} ((2.46^2+2.54^2+2.47^2)/3))$ thus gives a value of -7.925 dB. Similarly the S/N ratio values for Ra and Pc is calculated for all the experimental runs.

The mean and S/N ratio for each level of the cutting parameters is calculated as per the procedure discussed, and the summarized values called the main effects (response). The greater is the S/N ratio, the smaller is the variance of quality characteristics around the desired (the-Smaller-the-better) value. Therefore, the optimal level of the process parameters is the level with the highest average S/N ratio. Based on mean S/N ratio values, the optimal level setting is A3B1C2. i.e., the cutting speed is to set at 180 m/min, the feed rate has to be set at 0.1mm/rev and the depth of cut is to be 0.6 mm for the objective of minimum surface roughness.

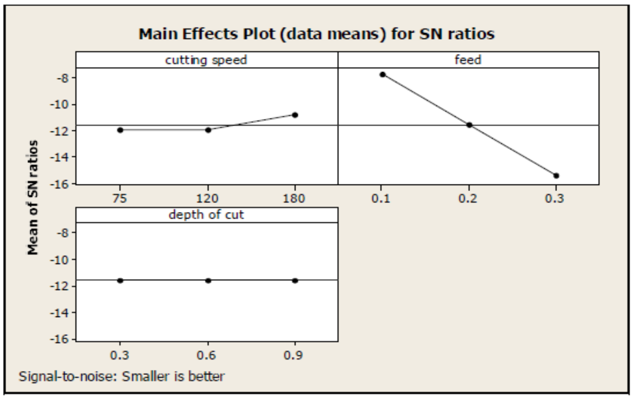

Fig.7 Main effects plot for surface roughness S/N ratio

Based on mean S/N ratio values for power consumption, the optimal level setting is A1B1C2 i.e., the cutting speed is to set at 75 m/min, the feed rate has to be set at 0.1mm/rev and the depth of cut is to be 0.6mm based on the experimental results for the objective of minimum power consumption.

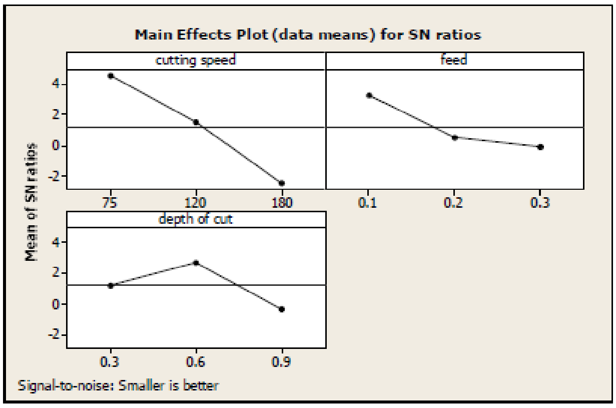

Fig.8 Main effects plot for power consumption S/N ratio

7.2 Analysis Of Variance (ANOVA)

Table 11 ANOVA for surface roughness S/N ratio

Source	DoF	SS	MS	F	%P
A	2	2.694	1.347	5.876	2.9342
B	2	88.66	44.33	193.4	96.565
C	2	0.001	6E-04	0.003	0.0014
Residual Error	2	0.458	0.229		0.4993
Total	8	91.81			100

Table 12 ANOVA for power consumption S/N ratio

Source	DoF	SS	MS	F	%P
A	2	75.82	37.91	151.3	69.34
B	2	19.25	9.626	38.42	17.61
C	2	13.77	6.886	27.49	12.6
Residual Error	2	0.501	0.251		0.46
Total	8	109.3			100

The F- test is being carried out for 95% confidence level to study the significances of the process parameter. The high F-value indicates that the factor is highly significant in affecting the response of the process. In our investigation, for the material Al-SiC_p (15P) MMC the feed rate (96.56%) is a highly significant factor and plays a major role in affecting the surface roughness of the machined surface. The depth of cut factor does not affect the surface roughness characteristic within the experimental region. The cutting speed (69.34%) is major influencing factor for the response of power consumption followed by feed rate (17.61%) and depth of cut (12.60%).

Conclusions

1) The optimum process parameter evolved with respect to minimization of surface roughness and power consumption are cutting speed of 75 m/min, feed rate of 0.1 mm/rev and depth of cut of 0.6 mm for Al-SiC_P (10P) MMC and for Al-SiC_P (15P) MMC.
2) Based on comparison of performance between 10% and 15% Al-SiC MMC on the responses, it is found that the Al-SiC_p (10P) MMC showing better performance based on multi-response criteria.
3) Power consumed is less at lower cutting speeds because of less friction between the tool and work piece interface.
4) Increase in the surface finish and minimization of the tool wear could be possible while machining MMCs at higher cutting speeds.
5) The surface finish of the machined samples deteriorates with increasing feed rates. The best surface finish is obtained at low values of feed rates and cutting speed.
6) It is also found that increase in percentage of

reinforcing SiC_p has no improvement in their mechanical properties rather than increase in the tool wear.

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