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Selection of optimal machining parameters for metal matrix composites using Taguchi Technique

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ABSTRACT

In this article a optimization technique is proposed for optimizing the responses such as surface roughness and cutting force in turning of nano alumina particulate reinforced LM25 aluminum alloy metal matrix composites. The optimum machining parameters selection is a very important task to the process planer to achieve desired surface roughness with minimum machining cost. In this study, the optimization effect of machining parameters on surface roughness and cutting force in finish turning operation was investigated by using the Taguchi method. The experimental studies were conducted under simultaneously varying cutting speed, feed, and depth of cut. An orthogonal array, the signal-to-noise (S/N) ratio, and the analysis of variance (ANOVA) were employed to study the performance characteristics in the turning of LM25 aluminum alloy metal matrix composites using uncoated cemented carbide cutting tool inserts. The optimum machining parameters are experimentally validated for minimization of surface roughness and minimization of cutting force.

Key word : Surface roughness, Cutting force, Optimization, Taguchi method

Introduction

Demand for developing metal matrix composites for use in high performance applications; have significantly increased in the recent times. Among these composites, aluminum alloy matrix composites attract much attention due to their lightness, high thermal conductivity, moderate casting temperature and others. Various kinds of ceramic materials, e.g. SiC, Al_2O_3, MgO and B_4C are extensively used to reinforce aluminum alloy matrices. Superior properties of these materials such as refractoriness, high hardness, high compressive strength, wear resistance etc. make them suitable for use as reinforcement in MMCs.

MMCs even though are manufactured through net shaping processes still machining is unavoidable especially finish machining. The main problem associated with Nano alumina reinforced with LM25 aluminium alloy MMCs is the difficulty in machining it due to the presence of hard abrasive reinforcement particles. Because of this, the tool wear rates are very high limiting the cutting speed as well as the tool life. This results in longer machining times as well as higher machining costs due to the short tool life. In machining of parts, surface quality is one of most specified technical requirements in order to achieve compact assembly of machined components. The major indication of surface quality on machined part is surface finish which directly relies on tool geometry and machining parameters. Tool geometry like nose radius, edge geometry, rake angle, etc., can be controlled by the tool manufacturer whereas machining parameters have to be optimized. In finish turning, tool wear becomes an additional parameter affecting surface quality of finished parts. The flank wear rate is high at low cutting speed due to the generation of high cutting forces. Hence it may be concluded that cutting force and surface finish may be two important responses that need to be monitored in the finishing operation. Cutting speed, feed and depth of cut are the three independent parameters that influence these two responses. However, these parameters need to be optimized in order to make the machining process economical. Especially with the advent of CNC machines, optimization is inevitable to the process planner in order to ensure the product quality and reduce the machining cost.

In general, optimization of machining parameters is very important to be competitive in the global business. Many researchers have attempted to optimize the machining parameters for most of the common workpiece materials. However, Nano MMCs are a new class of materials that are being developed and as such not much research has been carried out on the machining of the Nano MMCs.

This paper reports the research carried out to evaluate the performance of uncoated cemented carbide cutting tools during turning of nano alumina particulate reinforced metal matrix composites. The guidelines for choosing cutting data provided by the cutting tool manufacturers are usually general and are not sufficient for quality and cost effective machining of specific workpiece materials. The main objective of this paper is to optimize the machining parameters for possible improvement in the machining quality especially surface finish. The optimal values of the various machining parameters are determined through experimental investigation. The full factorial experimental design approach is utilized for experimental planning and ANOVA is employed to investigate the influence of machining parameters on the surface roughness and cutting force during turning operation. The results obtained from the experimental study are utilized for analyzing and evaluating the effects of various input constraints at the optimal point. The effects of various constraints on the objective function are also analysed through main effect plots.

By using these plots, significant effect of various input constraints on surface roughness and cutting force are highlighted. The selected optimal machining parameters and its effectiveness are experimentally validated.

Experimental procedure

Single pass finish turning operation is conducted in dry cutting condition in order to investigate the performance and study the wear mechanism of uncoated cemented carbide tools when machining nano alumina particulate reinforced metal matrix composites in the form of cylindrical bar stock of diameter 80 mm. The experiments were conducted on an all geared type lathe machine.

Work material

Nano alumina particulate reinforced LM25 aluminium alloy metal matrix composite consisting of 10% nano alumina and LM 25 aluminum alloy material is used as the work piece material in the present investigation. Test specimen was prepared from cylindrical bar of 270mm long and 80mm diameter.

Tool material

Uncoated cemented carbide inserts as per ISO specification SNMG 120408-QM H13A and tool holder CTANR 2525-M16 type were used for the turning trials under dry cutting condition. Because of the popularity of square shaped inserts in industries for machining hard materials, square shaped inserts have been chosen in this study

Experimental set-up

The tests were conducted under different cutting conditions using a Kirloskar Turnmaster all geared type lathe machine having 3HP/2.2 kW power. The cutting speed was derived from the measured spindle speed and the diameter of the surface of the workpiece. The tests were carried out without coolant at a varying depth of cut and feed rate. The levels were specified for each process parameter as given in Table 1. The parameter levels were chosen within the intervals recommended by the cutting tool manufacturer. Three process parameters at two and three levels led to a total of 18 tests for turning operation. After each test, the surface roughness were measured using a surface roughness tester and during machining the cutting force was measured using a Kistler Dynamometer (SN type).

Table 1: Levels of machining parameters for orthogonal array

Machining parameters	Level 1	Level 2	Level 3
Cutting speed 'V' (m/min)	100	--	125
Feed 'f' (mm/rev)	0.1	0.15	0.2
Depth of cut 'd' (mm)	0.5	0.75	1.0

Results and discussions

The plan of the experiment was developed for assessing the influence of the cutting speed (V), feed rate (f) and depth of cut (d) on the surface roughness (Ra) and cutting force (Fz). Table 2 illustrates the experimental results for Ra and Fz.

Table 2: Orthogonal array and experimental results

Machining parameters				Response variables		S/N ratio	
Trail No.	Cutting speed 'V' (m/min)	Feed 'f' (mm/rev)	Depth of cut 'd' (mm)	Surface roughness 'Ra' (µm)	Cutting Force 'Fz' (N)	Surface roughness	Cutting Force
1	100	0.1	0.5	1.03	48.84	-0.257	-33.776
2	100	0.1	0.75	0.8	29.22	1.938	-29.314
3	100	0.1	1	1.28	152.3	-2.144	-43.654
4	100	0.15	0.5	1.42	87.29	-3.046	-38.819
5	100	0.15	0.75	1.56	196.78	-3.862	-45.880
6	100	0.15	1	1.66	306.2	-4.402	-49.720
7	100	0.2	0.5	1.7	260.08	-4.609	-48.302
8	100	0.2	0.75	1.17	238.76	-1.364	-47.559
9	100	0.2	1	0.98	244.64	0.175	-47.771
10	125	0.1	0.5	1.01	44.36	-0.086	-32.940
11	125	0.1	0.75	0.97	146.65	0.265	-43.326
12	125	0.1	1	1.53	149.08	-3.694	-43.468
13	125	0.15	0.5	1.61	107.8	-4.137	-40.652
14	125	0.15	0.75	1.81	117.73	-5.154	-41.418
15	125	0.15	1	1.39	120.57	-2.860	-41.625
16	125	0.2	0.5	2.36	101.2	-7.458	-40.104
17	125	0.2	0.75	2.24	147.46	-7.005	-43.373
18	125	0.2	1	1.57	179.74	-3.918	-45.093

The experimental results were analyzed using analysis of variance (ANOVA) with the objective of identifying the factors significantly affecting the performance measures. The results of the ANOVA with the surface roughness and cutting force are shown in Table 3 and 4 respectively. This analysis was carried out for a significance level of $\alpha = 0.05$, i.e. for a confidence level of 95%. Tables 4 and 5 shows 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. Also, the last columns of the tables show the percent contribution of each source to the total variation indicating the degree of influence on the result. Table 3 shows that cutting speed, feed were individually dominates and feed interacts with other parameters have a statistically significant effect on the surface roughness whilst in Table 4 neither of the main nor interaction factors are statistically significant.

Table 3: Analysis of Variance for Surface roughness

Source Term	Degree of Freedom	Sum of Squares	Mean Square	F-Ratio	P-value	% Contribution
V	1	0.46401	0.46401	20.08	0.011*	14.96
f	2	1.10521	0.55261	23.92	0.006*	35.62
a	2	0.04858	0.02429	1.05	0.430	1.57
V*f	2	0.46454	0.23227	10.05	0.028*	14.97
V*a	2	0.07498	0.03749	1.62	0.305	2.42
f*a	4	0.85276	0.21319	9.23	0.027*	27.49
Residual Error	4	0.09242	0.02311			2.98
Total	17	3.10249				100.00
* Term significant at alpha = 0.05						

Table 4: Analysis of Variance for Cutting force

Source Term	Degree of Freedom	Sum of Squares	Mean Square	F-Ratio	P-value	% Contribution
V	1	11226	11226	3.10	0.153	10.96
f	2	30616	15308	4.22	0.103	29.90
a	2	21147	10574	2.92	0.166	20.65
V*f	2	17263	8632	2.38	0.209	16.86
V*a	2	3373	1687	0.47	0.658	3.29
f*a	4	4274	1068	3.10	0.153	4.17
Residual Error	4	14507	11226			14.17
Total	17	102406				100.00
* Term significant at alpha = 0.05						

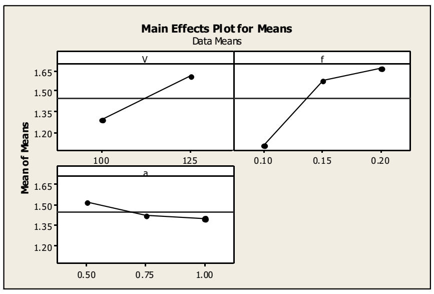
Analysis of Surface roughness

The surface roughness and cutting force have been individually analysed using MINITAB software. The mean S/N ratio for each level of the machining parameters was calculated and the results are shown in the Table 5. Based on the data and Fig.1 the optimal performance for the minimum surface roughness was obtained at level 1 - cutting speed (100 m/min), level 1 - feed (0.1mm/rev), and level 3 - depth of cut (0.50mm). Ranking of the machining parameters are also calculated based on difference in the S/N ratio and the rank indicates the dominant machining parameters that affect surface roughness. Fig.1 shows the plot for surface roughness, which indicates that surface roughness increases with increase of cutting speed and feed rate.

Table 5: Signal to Noise Ratio for Surface roughness

Details	Machining parameters Mean S/N ratio		
	Cutting speed	Feed	Depth of cut
Level 1	-1.9523	-0.6631	-3.2654
Level 2	-	-3.9101	-2.5303
Level 3	-3.7830	-4.0297	-2.8072
Delta	1.8308	3.3667	0.7351
Rank	2	1	3

Figure 1: Mean of Signal to noise ratio for Surface roughness



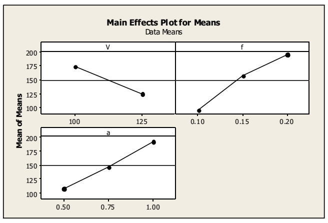
Analysis of cutting force

Cutting force is one of the most critical factors to decide the cost effectiveness of the machining process. Fig 2 shows that the cutting force decreases with increase of cutting speed due friction and tribological behaviour, whilst it increases with increase of feed and depth of cut. Based on the analysis using the Table 6, optimal performance for the minimum cutting force (Fig. 2) was obtained at level 3 - cutting speed (125m/min), level 1-feed (0.2mm/rev), and level 1 - depth of cut (1.0mm).

Table 6: Signal to Noise Ratio for Cutting force

Details	Machining parameters Mean S/N ratio		
	Cutting speed	Feed	Depth of cut
Level 1	-39.75	-34.74	-36.09
Level 2	-	-40.01	-38.80
Level 3	-38.32	-42.36	-42.21
Delta	1.42	7.62	6.12
Rank	3	1	2

Figure 2: Mean of Signal to noise ratio for cutting force



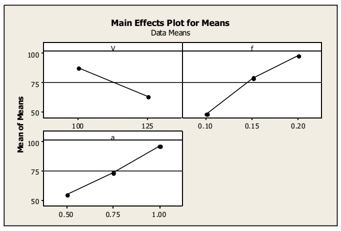
Simultaneous optimization of Surface roughness and Cutting force

In machining operation the minimum surface roughness as well as the minimum cutting force is an important and essential criteria for manufacturing economically. The earlier subsections have discussed the effect of optimizing a single response (i.e) either minimum surface roughness or minimum cutting force. However in reality both surface roughness and cutting force have to be optimized simultaneously [13, 14]. Among these two responses, surface roughness is to be given higher priority since it directly affects the part quality. In Taguchi technique this can be achieved by giving higher weightage to cutting force than surface roughness. Based on Fig.3, combined effect of cutting force with surface roughness decreasing with increase of cutting speed whereas feed and depth of cut have maximum influences the both responses. From Table 7 and Fig.3 the optimal cutting parameters for the both minimizing objectives were obtained at level 3 - cutting speed (125m/min), level 1 - feed (0.1mm/rev), and level 1- depth of cut (0.5 mm).

Table 7: Signal to Noise Ratio for Surface roughness with Cutting force

Details	Machining parameters Mean S/N ratio		
	Cutting speed	Feed	Depth of cut
Level 1	-39.75	-34.74	-36.09
Level 2	-	-40.01	-38.80
Level 3	-38.32	-42.36	-42.21
Delta	1.42	7.62	6.12
Rank	3	1	2

Figure 3: Mean of Signal to noise ratio for simultaneous optimization of surface roughness and cutting force



Validation experiments

Table 8 presents the results from the validation experiments, which exhibit a good consistency between the predicted and the actual responses.

Table 8 Predicted result with experimental validation

Prediction method	Machining parameters			Surface roughness 'Ra' (μm)			Cutting force 'Fz' (mm)		
Taguchi Analysis	Cutting speed 'v' m/min	Feed 'f' mm/rev	Depth of cut 'a' mm	Predicted 'Ra'	Actual 'Ra'	Error (%)	Predicted 'Fz'	Actual 'Fz'	Error (%)
Optimization for surface roughness	100	0.1	1.00	1.41	1.28	9.2	150	152	1.3
Optimization for Cutting force	125	0.1	0.5	1.06	1.02	3.8	66	68	2.94
Simultaneous optimization	125	0.1	0.5	-	1.0		-	65	

Conclusion

L18 orthogonal array based designs of experiments were conducted and Taguchi optimization analyses were carried out for predicting the optimum cutting conditions. Based on the experimental and analytical studies following conclusions are drawn.

- Based on Taguchi design of experiments and analysis, the feed is the main factor that has the highest influence on surface roughness as well as cutting force.
- An optimum machining condition for minimum surface roughness was determined by Taguchi analysis. The percentage error between actual and predicted result for surface roughness is 9.2% and for the same condition the error in cutting force prediction is 1.3%.
- Similarly, for minimum cutting force, the percentage error between actual and predicted result for cutting force is 2.94% and for the same condition, the error in surface roughness is 3.8%.
- Simultaneous optimization for minimum surface roughness and minimum cutting force was determined. A cutting speed of 125m/min, a feed rate of 0.1mm/rev and a depth of cut of 0.5mm seems to be the best combination of cutting condition leading to lower values for both surface roughness and cutting force.

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