

Evaluation of Surface Roughness and Material Removal Rate in End Milling of Complex Shape

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Abstract In this work, an attempt has been made to analyze the influence of various machining input parameters of CNC end milling process viz. cutting speed, feed rate and depth of cut on machining output variables (surface roughness and material removal rate) during machining complex shape of copper. Three different levels of input parameters were planned as per Taguchi's L_9 orthogonal array. The parameters are optimised from analysis of mean (ANOM). Analysis of variance (ANOVA) was employed to investigate the effect of machining parameters on the variables. Results of this study indicate that the depth of cut has the most significant effect on R_a having percentage contribution of 71.06% followed by feed rate and cutting speed having percentage contribution of 23.22% and 2.12% respectively. For material removal rate, it is observed that the percentage contribution of feed rate is maximum i.e. 68.58% followed by depth of cut and cutting speed having percentage contribution of 22.13% and 7.52% respectively. Also, the results revealed that optimum combination of machining parameters which resulted in optimum value of the surface roughness is $A_3B_1C_2$ i.e. cutting speed of 6000 rpm, feed rate of 500 mm/tooth and depth of Cut of 0.06 mm. Similarly, optimum combination of machining parameters which resulted in optimum value of material removal rate is $A_1B_3C_3$ where the values for cutting speed, feed rate and depth of cut are 2000 rpm, 1500 mm/tooth and 0.08 mm respectively.

Keywords End Milling, Surface Roughness, Material Removal Rate, Copper, Optimization

1. Introduction

Surface roughness and material removal rate are two important aspects during machining which involve attention both from manufacturing as well as research and development point of view. In recent industry, one of the tendencies is to produce low cost, high quality products in short time [1]. The roughness of the machined surface is considered as the important aspect affecting on the quality of the product, function, and reliability [2-5]. On the other hand,

the material removal rate is another important aspect in improving machining performance, effecting on the productivity and reduced lead times and cost [6]. It is very difficult for an operator to select optimum machining parameters to achieve best surface finish and higher productivity. Therefore, many researchers have focused on the effect of machining parameters and selection the optimum values of these parameters to determine best surface finish and highest value of material removal rate [1, 7]. In this research an attempt has been made to produce complex shapes using vertical milling operation through end milling process. The specific objectives of the study are: to understand milling machine and various milling operations; to investigate the effect of various machining parameters on surface roughness and material removal rate; and to optimize the machining parameters. Experiments have been carried out according to Taguchi's L_9 orthogonal array (OA) on a CNC vertical milling machine. The details of the procedure are discussed in the following sections.

2. Materials

In this research, a workpiece made of a copper with high purity (99.9% Cu) was used. Pure copper is hard to machine due to high ductility, while machining the cutting force on the rake face of the tool increases too much which leads to an overall increase in the cutting forces. Pure copper finds its application in making the pipes that are used in heat exchangers and also in electrical applications such as switches and electrical boards that have features such as holes, slots and pockets which are produced by machining. . Many applications for electronic and manufacturing industry require microstructural stability and high temperature resistance materials, good mechanical properties, high electrical conductivity and corrosion resistance. For such applications, the most promising metal is copper because of its high electrical and thermal conductivity [8]. Table 1 shows the chemical composition of copper which was used in this research. High speed steel and cemented carbide tools were employed as the cutting tool material. The end milling operation was carried out by using end mill cutter and ball mill cutter (8mm).

Table 1. Chemical composition of copper

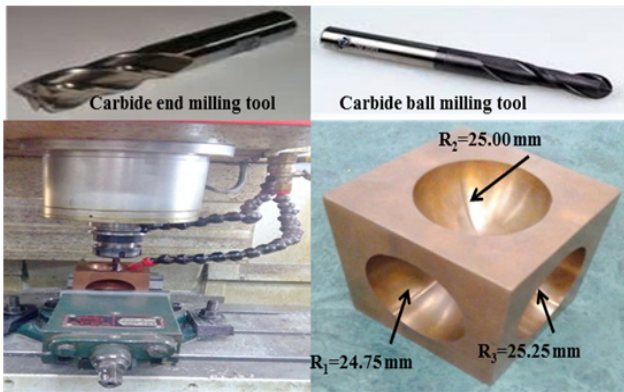
Elements	Copper	Tin	Lead	Iron	Nickel	Manganese	Cobalt	Silver	Phosphorus	Zinc
Composition %	99.90	0.024	0.004	0.002	0.002	< 0.001	< 0.001	0.001	0.040	0.017

3. Experimental Method

From a bar, copper cube of 80 mm was cut by power hacksaw and face milling was carried out on vertical CNC milling machine using face milling cutter. Then, the experiments were carried out on vertical CNC milling machine by using different machining parameters of L_9 orthogonal array. The machining parameters and their levels used in present study as shown in Table 2. Nine hemispherical shapes (Complex Shape geometry) were formed on nine faces of two cubes, 6 hemispheres on 6 faces of one cube and 3 on the other cube, using end milling cutter and for better surface finish, ball milling cutter of 8 mm was used. Each hemisphere has three different Radii (24.75 mm, 25 mm and 25.25 mm) as shown in the Figure 1. Surface roughness values were measured by surface roughness tester (SURTEST SV-2100; make: Mitutoyo, Japan). During machining, the material removal rate was calculated against recorded "time of cut".

Table 2. Machining parameters and their levels

Factors	Symbol	Level 1	Level 2	Level 3
Speed (rpm)	A	2000	4000	6000
Feed rate (mm/tooth)	B	500	1000	1500
Depth of cut (mm)	C	0.04	0.06	0.08

**Figure 1.** milling operation of copper cube

4. Taguchi Design of Experiment

In this study, experiments based on Taguchi L_9 orthogonal array were performed to determine the best levels of the process parameters. The greatest advantages of the Taguchi method are to decrease the experimental time, to reduce the cost and to find out significant factors in a shorter time

period [9, 10]. Taguchi used the S/N ratio as the quality characteristic of choice to analyze the data [11-13]. The methods for calculating the S/N ratio are classified into three main categories, depending on whether the desired quality characteristics are smaller the better, larger the better or nominal the better. In the case of surface roughness, the smaller values are always considered and in case of material removal rate, the larger values are always considered. The Eq.1 and Eq.2 were applied for calculating the S/N ratio for smaller the better characteristics and larger the better characteristics respectively.

$$S/N = -10 \log \frac{1}{n} \sum_{i=1}^m y_{ij}^2 \quad (1)$$

$$S/N = -10 \log \frac{1}{n} \sum_{i=1}^m \frac{1}{y_{ij}^2} \quad (2)$$

5. Results and Discussion

In this section, an ANOVA is conducted to analyze the experimental results and identify statistically significant trends in the surface roughness and material removal rate data.

5.1. Analysis for Surface Roughness

Table 3 shows the experimental results and corresponding S/N ratio for surface roughness (R_a) using the relation for lower the better. Table 4 shows the analysis of mean (ANOM) for surface roughness. From Table 3, it is observed that optimized level for surface roughness is $A_3 B_1$ and C_2 . Moreover, the depth of cut (C) having the largest values of difference between maximum and minimum values among the three parameters. The main effects plots for surface roughness were constructed. As may be observed also from Figure 2 that the optimal combination of machining parameters is $A_3 B_1 C_2$ i.e. the minimum value of surface roughness is obtained at speed of 6000 rpm, feed rate of 500 mm/tooth and depth of cut of 0.06 mm. ANOVA results for surface roughness are given in Table 5. From Table 5 it can be noticed that the depth of cut has maximum influence on the R_a with the contribution 71.60%, followed by feed rate and cutting speed with contributions 23.22% and 2.12% respectively. It may be due to fact that the tool chip contact length increases with increasing depth of cut causing increase in the chip width leading to increase in the cutting forces and temperature which in turn effect on the surface roughness values. These results agree with previous studies [3, 14].

Table 3. Experimental results and S/N ratios values for surface roughness

Expt. no.	A	B	C	R _a (y _i)	S/N	h ²
1	2000	500	0.04	0.2535	11.92	142.097
2	2000	1000	0.06	0.157	16.08	258.631
3	2000	1500	0.08	0.243	12.29	150.992
4	4000	500	0.08	0.201	15.65	244.923
5	4000	1000	0.04	0.29	10.75	115.606
6	4000	1500	0.06	0.206	13.72	188.311
7	6000	500	0.06	0.152	16.36	267.752
8	6000	1000	0.08	0.17	15.39	236.884
9	6000	1500	0.04	0.299	10.49	109.968
Total					122.66	1715.16

Table 4. Analysis of mean (ANOM) for surface roughness

Factor	Symbol	Unit	Level-1	Level-2	Level-3	Max	Min	Max-Min
speed	A	rpm	13.43	13.37	14.08	14.08	13.37	0.71
feed rate	B	mm/tooth	14.64	14.08	12.17	14.64	12.17	2.48
depth of cut	C	mm	11.05	15.39	14.44	15.39	11.05	4.34

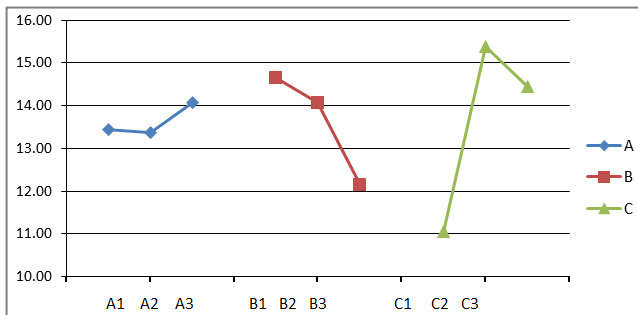


Figure 2. The main effect plot for S/N ratio for Surface Roughness

Table 5. ANOVA results for surface roughness.

Source	Sum of sequence	DF	Mean square	F ratio	% Contribution
A	0.92	2	0.46	0.69	2.12
B	10.11	2	5.06	7.59	23.22
C	31.19	2	15.60	23.41	71.60
Error	1.33	2	0.67		3.06
Total	43.56	8			100.00

5.2. Analysis for Material Removal Rate

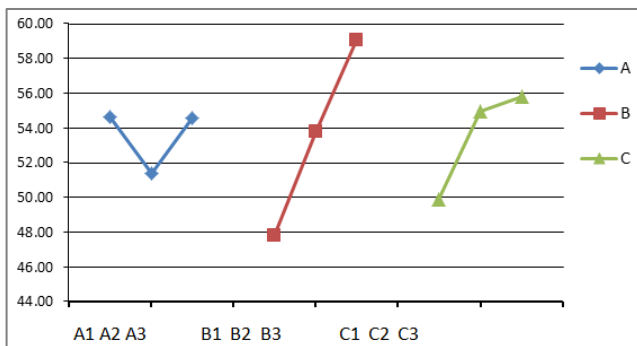
Experimental results of the material removal rate are shown in Table 6. The analysis of mean for MRR is shown in Table 7. It is observed from Table 7 that the feed rate having the highest values of difference between maximum and minimum among the three parameters. From above observation it is further concluded that feed rate being the highest value, is the most significant parameter for material removal rate. It can be derived also from Figure 3 that the optimal combination of machining parameters is A₁ B₃ C₃ i.e. the maximum value of MRR is obtained at 2000 rpm of speed, 1500 mm/tooth of feed rate and 0.08 mm of depth of cut. ANOVA results for MRR are given in Table 8. It can be seen from Table 8 that the feed rate has maximum influence on the MRR with the contribution 68.58%, followed by depth of cut and machining speed with contributions 22.13% and 7.52% respectively. Since the feed rate is the speed of the cutting tool's movement relative to the workpiece as the tool makes a cut and the size removed of chip per tooth increases with increasing the feed rate. Therefore, the material removal rate increases significantly with increasing feed rate.

Table 6. Experimental results and S/N ratios values for material removal rate

Exp. no.	A (rpm)	B (mm/tooth)	C (mm)	MRR	S/N	h ²
1	2000	500	0.04	206.6890	46.31	2144.278
2	2000	1000	0.06	615.52	55.78	3111.949
3	2000	1500	0.08	1235.45	61.84	3823.753
4	4000	500	0.08	233.46	47.36	2243.372
5	4000	1000	0.04	236.34	47.47	2253.472
6	4000	1500	0.06	927.29	59.34	3521.747
7	6000	500	0.06	307.87	49.77	2476.789
8	6000	1000	0.08	801.83	58.08	3373.478
9	6000	1500	0.04	622.66	55.89	3123.135
Total					481.84	232170.8

Table 7. Analysis of Mean (ANOM) for material removal rate

Factor	Symbol	Unit	Level-1	Level-2	Level-3	Max	Min	Max-Min
Speed	A	rpm	54.64	51.39	54.58	54.64	51.39	3.25
Feed rate	B	mm/tooth	47.81	53.78	59.02	59.02	47.81	11.21
Depth of cut	C	mm	49.89	54.97	55.76	55.76	49.89	5.87

**Figure 3.** The main effect plot for S/N ratio for material removal rate**Table 8.** ANOVA results for material removal rate.

Source	Sum of sequence	DF	Mean square	F ratio	% Contribution
A	20.71	2	10.35	4.26	7.52
B	188.73	2	94.37	38.81	68.58
C	60.92	2	30.46	12.53	22.13
Error	4.86	2	2.43		1.77
Total	275.22	8			100.00

6. Conclusions

In this study, milling operations of complex shape on difficult to machine material i.e. copper were conducted. The effect of three machining parameters viz. speed, feed rate and depth of cut on the two response variables namely surface roughness and material removal rate were investigated. Taguchi's design i.e. L₉ orthogonal array was used to obtain optimum machining parameters.

Subsequently, ANOVA was applied to investigate the effect of machining parameters on R_a and MRR and to obtain the percentage distribution of the parameters. From the results of the present study the following conclusion are drawn: (i) The optimum combination of machining parameters and their levels for decreasing the deviation in R_a and MRR are A₃B₁C₂ and A₁B₃C₃ respectively; (ii) depth of cut significantly affects R_a; the percentage contribution of depth of cut, feed rate and speed are 71.60%, 23.22%, 2.12% respectively; (iii) feed rate significantly affects MRR, the percentage contribution of feed rate, depth of cut and speed are 68.58%, 22.13% and 7.52% respectively.

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