Optimization of surface characteristics of copper using novel powder metallurgy alloy tool

[1]P Kishore, [2]P Manoj Kumar, [3]S N Dinesh

[1]Assistant Professor, [2]Assistant Professor, [3]Assistant Professor
Mechanical Engineering Department
KPR Institute of Engineering and Technology, Coimbatore, India

***Abstract*— In manufacturing nowadays, Powder metallurgy has turn out to be competitive with the processes such as casting, forging and machining predominantly for intricate parts made of high-strength and hard alloys. The aim is to revise the viability of cutting tool (Fe - 1%C – 2%W – 1%Ti) made-up by the Powder Metallurgy process. Sintered cylindrical preforms are hot forged at superior temperature and it is machined off to the standard single point cutting tool. After the tool ground to the required geometry, hardness of the P/M alloy tool is enhanced by Induction Hardening process. Taguchi method is used to investigate changes in surface roughness caused on the work material surface during turning operation by the P/M alloy tool and HSS tool under various machining conditions. The orthogonal array, the signal-to-noise ratio, and the analysis of variance are employed to study the performance characteristics of P/M alloy tool and HSS tools in turning Copper as work piece. The cutting parameters namely cutting speed, feed rate, and depth of cut are used to find the condition to minimize the surface roughness using signal-to-noise ratio. Experimental results are analyzed to demonstrate the efficiency of this approach.**

Keywords: Forging, Induction Hardening, Hardness, Machining, Surface roughness.

I. INTRODUCTION

Powder metallurgy (P/M) technique is a forming process with capabilities of profitable manufacture of small parts, with tailor-made properties. P/M components locate wide-ranging applications in automotive, defense, aerospace, etc., due to their superior metallurgical and mechanical properties, as a result of advanced technology. The parts made by powder metallurgy are extensively harder than conventional technique. This is a new attempt to manufacture a novel cutting tool from powder metallurgy process. Optimization was done by using Taguchi optimization technique. Aravind et al.[1] studied the machining parameters of turning of 11SMn30Alloy to optimize the input parameters in turn improvise the process capability index in terms of surface roughness(Ra, Rz). Taguchi method was used for optimization and carbide cutting tool have been used. It was concluded that the feed rate and cutting speed are the influential parameters and their optimized values were 0.2 mm/rev and 80 m/min for surface roughness Ra. For the surface roughness Rz, the values were found to be 0.15 mm/rev and 160 mm/min respectively. G Kant et al.[3] proposed a multi-objective predictive model for the reducing the power consumption and surface roughness while machining AISI 1045 steel. It was observed that the feed rate in the imperative parameter for minimizing the power consumption and improving the surface finish during machining. Rajendra et al. [5] made an effort to optimize the material removal rate taking feed rate, cutting speed and depth of cut as the influential process parameters in turning of Al-6061. Signal to noise ratio was used to carry out the analysis. This study predicted that the depth of cut is not the significant factor in increasing material removal rate but the feed rate controls it. An attempt has been made to optimize the various process parameters for improving the surface finish while turning the titanium alloy by Ramana et al.[6]. The experiment disclosed that uncoated tool is appropriate for low cutting speeds and PVD coated tools are fit for more cutting speeds. Also it was revealed that feed rate is the dominating factor to improve surface finish for both uncoated and PVD coated tools. Durairaj et al. [8] studied CNC Micro turning of Inconel 600 alloy with titanium carbide coated tool with various combination of process parameters to optimize the surface roughness and tool wear. They used a multi-objective optimization method based genetic algorithm for this purpose. Shreemoy Kumar Nayak et al.[9] studied the influence of machining parameters on material removal rate, cutting force and surface roughness. Simultaneously they made an attempt to optimize them with the help of grey relational analysis. Their study explored the optimum parametric combination based on their experiment. A. Torres et al. [2] investigated the surface roughness of 2030-T4 aluminium alloy in dry turning operation. This study revealed that the collaborative effect between the depth of cut and the feed rate was the important parameter for dry turning operations. Deepak and Beedu Rajendra [4] determined feed rate is the influential parameter for surface roughness during turning of Aluminum 6061. They found that increase in feed rate and depth of cut is key factor for enhancing the surface roughness. Vinayagamoorthy et al. [7] analyzed the performance of precision turning using conventional lathe on Ti-6Al-4V while the working condition was dry. They used grey rational method for this purpose. Hence, from above literature Taguchi is a powerful tool for optimization of process parameter. This is a new attempt to manufacture a cutting tool to improve the surface quality in turning operation than the conventional tool. Following study will briefly discuss the fabrication and performance of novel tool.

II. FABRICATION OF CUTTING TOOL

Elemental powders of iron, carbon, titanium and tungsten were perfectly weighed and systematically mixed in an ball mill for 10 h to yield the alloy compositions of Fe - 1%C – 2%W – 1%Ti). Blended powders were then compacted into cylindrical preform of size Ø25 X 33 mm, by means of 1000 KN Universal Testing Machine (UTM). After compaction aluminium coating was applied to prevent the oxidation. Sintering was done at muffle furnace at 1000°C for a period of 30 min. Figure 1.a shows the sintered preform. The sintered preforms is then hot forged at elevated temperature of 1200°C to get powder metallurgy (P/M) cutting tool of required size 12*12mm using 200T friction screw forging machine. Then it is rapidly quenched in SAE 60 oil to increase the hardness. In order to improve the hardness of the tool equivalent to HSS tool, P/M tool is further hardened by induction hardening process by heating the tool to 850°C then it is rapidly cooled in SAE 60 oil. The hardness of the tool is improved by 17%. Then tool is machined to required tool geometry to get single point cutting tool. Figure 1.b shows the hardened powder metallurgy cutting tool. Table 1 shows the hardness of P/M tool at various stages.

Table 1 The hardness of P/M tool at various stages

S. No	P/M tool	Rockwell C scale
1	Sintered preform	32 – 36 HRC
2	Sinter-Forged	46 – 54 HRC
3	Sinter-Forged Hardened	62 – 68 HRC

This hardened single point P/M cutting tool is taken for further study to preform machining operation with copper and in order to compare the effectiveness of the P/M cutting tool, copper is machined with standard HSS tool. The surface roughness is taken as a response parameter. Surface roughness values obtained from two different cutting tools were discussed elaborately in this paper.

Fig. 1.a Sintered preform

Fig. 1.b Hardened Tool

III. EXPERIMENTAL DESIGN

Work material

Copper of ASTM b1 standard with Brinell hardness 42 which is used for electrical purposes was taken as a work material is taken to perform turning operation with HSS tool and P/M Tool. Copper of uniform diameter of 30 mm and 48 mm length was taken for the experiment.

Machining Condition

The dry turning test was conducted on Copper using P/M tool and HSS tool by varying the cutting speed, feed rate and depth of cut on all geared headstock crown lathe. The speed of the spindle varies from 60- 1050 rpm. The machining parameters are shown in Table 2

Table 2 Machining Parameters

Speed (RPM)	Cutting speed (m/min)	Feed Rate (mm/rev)	Depth of cut (mm)
202	40.61	0.117	0.4
303	60.92	0.292	0.6
455	91.48	0.583	0.8

Taguchi design

Taguchi method consists of a plan of experiment with the purpose of acquiring in optimum way, executing these experiments and analysing data, in order to obtain information about the behaviour of a given process. Orthogonal arrays are used to define the experimental plans and the analysis of the results is based on the analysis of variance. The experimental plan using Taguchi method was made using the 3 factors considered with the 3 levels of those factors. According to Taguchi design a L9 orthogonal array was chosen for the experiments to reduce the number of runs and cost. The plan is made of nine tests of experiments in which the first column was assigned to the cutting velocity, the second column to the feed rate and the third depth of cut. In Taguchi method, process parameter which influence the surface roughness are broken up into two group; noise factor and control factors. The variation which occurs during the experiment is denoted by using noise factor. The control factors indicate the best combination for steadiness in manufacturing process. Based on Taguchi methodology the smaller the better characteristics are chosen, smaller the value of surface roughness obtains the best combination. S/N ratio formula for smaller-the-better characteristics is indicated in eqn.1.

$$\text{Smaller-the-better} = -10 * \log 10 \left[\sum y^2 / n \right] \quad (1)$$

Where, n is the number of observations and y is the observed data.

IV. RESULT AND DISCUSSION

The experiment was conducted using all geared headstock crown lathe using P/M tool and HSS tool by machining copper. The parameters selected for the experiment are cutting speed, feed rate and depth of cut. The response parameter is surface roughness obtained by machining copper using P/M tool and HSS tool. Figure 2 shows the machining of copper. Table 3 shows the L9 Taguchi orthogonal array design and the response value for the design. Surface Roughness is measured by means of Mitutoyo SJ-210 Portable Surface roughness tester of 2µm stylus tip radius. The measuring force of the stylus is 0.75mN with 0.25mm/s speed. The conical taper angle of detector is 90̊. The value of surface roughness (Ra) was calculated by taking the average of three different trails. Figure 3 shows the surface roughness tester. In this experiment all the design plot and the analysis were carried out using Minitab 17 statistical software. Lower the value of surface roughness gives the optimum machining parameter therefore smaller the better characteristics is selected to calculate the S/N ratio value for P/M tool and HSS tool while machining copper.

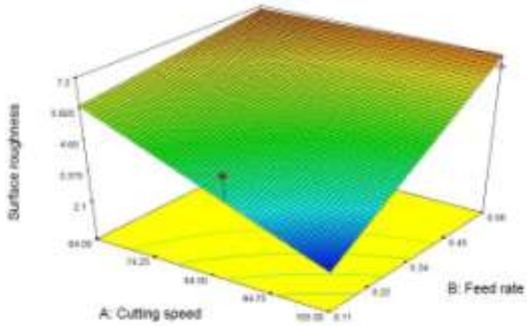
Fig. 2 Turning of copper

Table 3 Response characteristics of P/M tool and HSS tool.

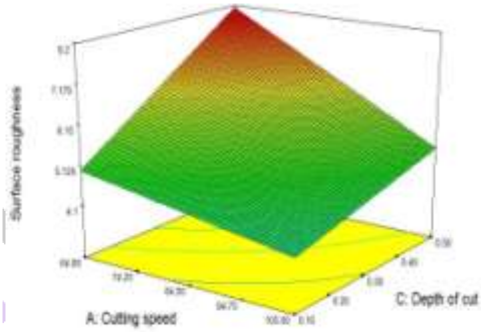
Cutting Speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Ra for P/M tool (µm)	Ra for HSS tool (µm)
64	0.112	0.1	3.76	4.05
64	0.235	0.3	4.67	5.72
64	0.562	0.5	7.52	7.86
88	0.112	0.3	4.82	4.87
88	0.235	0.5	7.52	7.98
88	0.562	0.1	7.92	8.02
105	0.112	0.5	2.98	3.16
105	0.235	0.1	2.03	2.76
105	0.562	0.3	6.74	7.2

Fig. 2 Portable Surface Roughness tester.

From the table 3 it is clear that surface roughness characteristics for P/M tool and HSS tool is poor at lower cutting speed and higher feed rates. The maximum surface roughness value for P/M tool is 7.92 and for HSS tool is 7.98. From the table 3 it is seen that surface roughness value obtained by P/M tool is better than HSS tool. Figure 4 and 5 shows the 3-D surface roughness plot with respect to P/M tool and HSS tool. The 3-D graph were analysed by using design expert software. From the Figure 4 and 5 it is clear that optimum surface were obtained at maximum cutting speed, minimum feed rate and minimum depth of cut. Figure 4 (a) shows the surface roughness characteristics of cutting speed and feed rate. Figure 4 (b) shows the surface roughness characteristics of cutting speed and depth of cut. Figure 4 (c) shows the surface roughness characteristics of feed rate and depth of cut. From these entire three graph it is clear that high-quality of surface roughness is obtained at maximum cutting speed, minimum feed and depth of cut. Similarly from the graph 5 (a), (b) and (c) the superior surface roughness is obtained at maximum cutting speed, minimum feed rate and minimum depth of cut.



(a)



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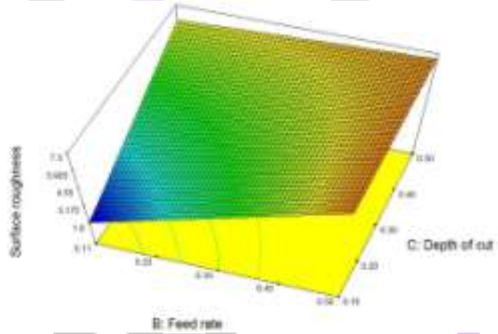
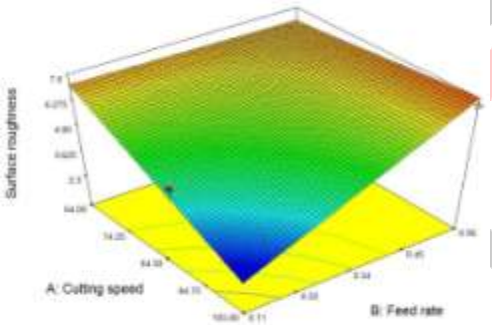
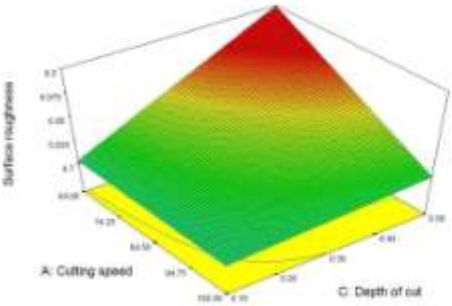


(c)

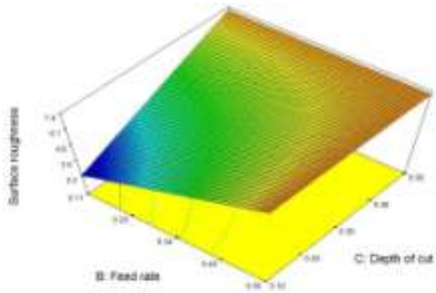
Fig. 4 Surface roughness characteristics of P/M tool (a) Cutting speed and Feed rate (b) Cutting speed and Depth of cut (c) Feed rate and Depth of cut.



(a)



(b)



(c)

Fig. 5 Surface roughness characteristics of HSS tool (a) Cutting speed and Feed rate (b) Cutting speed and Depth of cut (c) Feed rate and Depth of cut.

Signal to noise ratio

Taguchi method consists of a plan of experiment with the purpose of acquiring in optimum way, executing these experiments and analysing data, in order to obtain information about the behaviour of a given process. Orthogonal arrays are used to define the experimental plans and the analysis of the results is based on the analysis of variance. The experimental plan using Taguchi method was made using the 3 factors considered with the 3 levels of those factors. According to Taguchi design a L9 orthogonal array was chosen for the experiments to reduce the number of runs and cost. In order to determine the effects of turning parameters if P/M tool and HSS tool Taguchi method is used. According to Taguchi process parameters are split up into two groups one is control factor and another one is noise factor. The control factors are used to choose the most excellent conditions for steadiness in design or manufacturing process, while the noise factors indicate all factors that cause variation. According to Taguchi method, the characteristic that the smaller value denotes the superior machining performance, such as optimal value Surface roughness can be achieved at smaller-the-better characteristics. The signal-to-noise ratio is analyzed by using MINITAB 17 statistical software. S/N ratio formula for smaller-the-better characteristics is indicated in eqn.1.

Smaller-the-better = $-10 * \log 10[\sum y^2/n]$ (1)

Where, n is the number of observations and y is the observed data.

Table 4 shows the S/N ratio of surface roughness machined using P/M tool. Fig. 6 shows the Main effect plot for S/N ratio. From the figure 6 it is clear that optimal combination of surface roughness to get minimum value are cutting speed = 105 m/min, feed rate = 0.112 mm/rev and Depth of cut = 0.1 mm.

Table 4 S/N ratio for P/M tool

Cutting Speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Ra for P/M tool (μm)	S/N RATIO
64	0.112	0.1	3.76	-11.5038
64	0.235	0.3	4.67	-13.3863
64	0.562	0.5	7.52	-17.5244
88	0.112	0.3	4.82	-13.6609
88	0.235	0.5	7.52	-17.5244
88	0.562	0.1	7.92	-17.9745
105	0.112	0.5	2.98	-9.48433
105	0.235	0.1	2.03	-6.14992
105	0.562	0.3	6.74	-16.5732

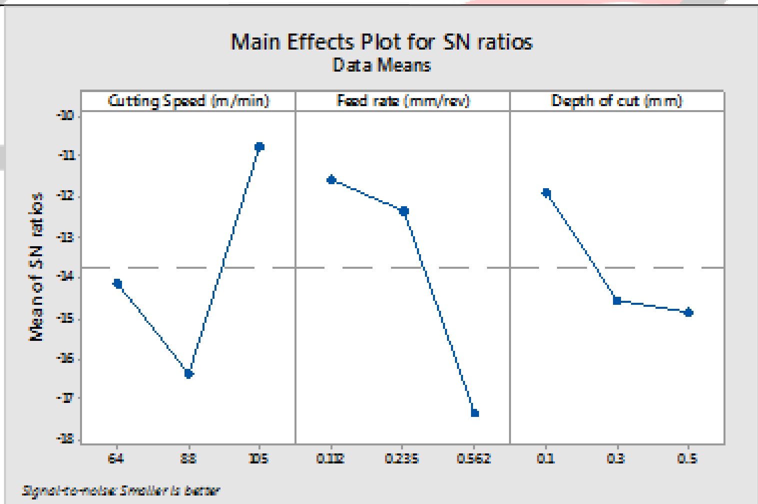


Fig. 6 Main effect plot for S/N ratio

Similarly Table 5 shows the S/N ratio of surface roughness machined using HSS tool. Fig. 7 shows the Main effect plot for S/N ratio. From the figure 7 it is clear that optimal combination of surface roughness to get minimum value are cutting speed = 105 m/min, feed rate = 0.112 mm/rev and Depth of cut = 0.1 mm.

Table 5 S/N ratio for P/M tool

Cutting Speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Ra for HSS tool (µm)	S/N RATIO
64	0.112	0.1	4.05	-12.1491
64	0.235	0.3	5.72	-15.1479
64	0.562	0.5	7.86	-17.9085
88	0.112	0.3	4.87	-13.7506
88	0.235	0.5	7.98	-18.0401
88	0.562	0.1	8.02	-18.0835
105	0.112	0.5	3.16	-9.99374
105	0.235	0.1	2.76	-8.81818
105	0.562	0.3	7.2	-17.1466

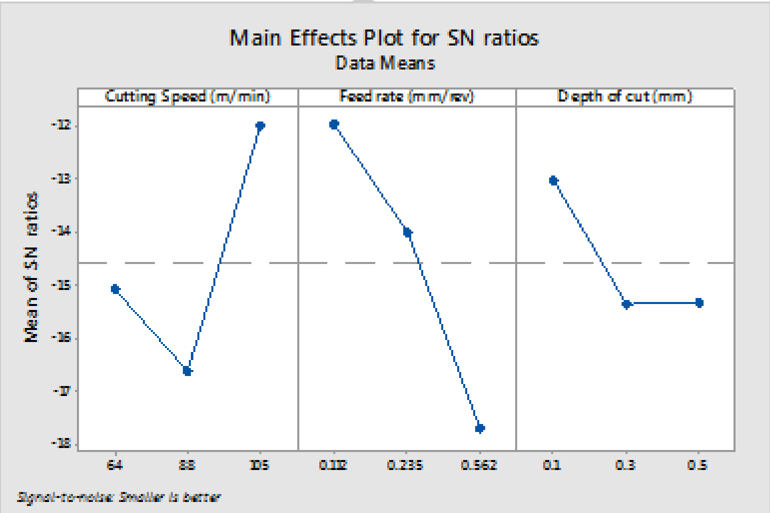


Fig. 7 Main effect plot for S/N ratio

For both the cutting tool on machining copper in Table 3, obtained surface roughness values and the S/N ratio analysis plots are similar. By comparing the value of surface roughness obtained by P/M tool and HSS tool, the surface roughness value obtained by P/M tool is better than HSS tool. In 3-D graph the P/M tool performance characteristics is better than HSS tool. Hence the tool fabricated from powder metallurgy (Fe - 1%C – 2%W – 1%Ti) can be used as single point cutting tool.

ANOVA

Analysis of variance (ANOVA) is useful in calculating the contribution of process parameters to the responses. In this study, ANOVA is calculated for both P/M tool and HSS tool of cutting speed, feed rate and depth of cut on surface roughness and tool wear. This analysis was made by means of 95% confidence level and 5% significance level. The factor with a maximum value of F –value contributes maximum rate to the overall contribution. From the Table 6 it is clear that Feed rate is the most influencing factor for surface roughness obtained by machining with P/M tool with the percentage of 57.27% followed by the cutting speed of 33.9% and depth of cut 8.76%. From the Table 7 it is clear that Feed rate is the most influencing factor for surface roughness obtained by machining with HSS tool with the percentage of 72.29% followed by the cutting speed of 30.05% and depth of cut of 61.95%. In the present work, Minitab 17 was used to ANOVA.

Table 6 ANOVA for P/M tool

Source	Df	Adj ss	Adj ms	F-value	P-value	Contribution %
Cutting Speed	2	12.071	6.035	5.23	0.160	33.9
Feed Rate	2	20.358	10.179	8.82	0.102	57.27
Depth Of Cut	2	3.126	1.563	1.35	0.425	8.76
Error	2	2.307	1.154			
Total	8	37.861				

Table 7 ANOVA for HSS tool

Source	Df	Adj ss	Adj ms	F-value	P-value	Contribution %
Cutting Speed	2	10.100	5.050	4.25	0.191	30.05
Feed Rate	2	20.445	10.223	8.60	0.104	72.29
Depth Of Cut	2	3.068	1.534	1.29	0.437	61.95
Error	2	2.378	1.189			
Total	8	35.992				

Based on the responses the regression equation has been developed using the MINITAB 17 software. Eqn. 2 and 3 shows the regression equation for the values of surface roughness in machining operation by P/M tool and HSS tool. A confirmation test has been carried out to determine the effectiveness of the approach. Table 8 shows the values of confirmation test of optimal combination (cutting speed v= 105 m/min, feed rate f = 0.112 mm/rev and Depth of cut d= 0.1 mm). And the corresponding predicted value of the optimal combination. The deviation of surface roughness value from predicted from the regression equation and the experimental value are less than 5%. Hence the regression equation 2 and 3 can be used for predicting the values of different process parameters.

Surface roughness for P/M tool = $Ra = 4.25 - 0.0279 \times v + 7.92 \times f + 3.59d$ (2)

Surface roughness for HSS tool $Ra = 4.99 - 0.0313 \times v + 7.86 \times f + 3.48d$ (3)

Table 8 Actual Vs Predicted

Optimal Condition	Surface Roughness	Experimental	Prediction	Error %
V, f, and d	P/M	2.25	2.55	3
	HSS	2.65	2.93	2.8

V. CONCLUSION

The following conclusion are made based on the performance of the single point cutting tool made from powder metallurgy process

- P/M alloy cutting tool (Fe - 1%C – 2%W – 1%Ti) shows superior surface roughness characteristics than the conventional HSS tool in the dry turning of copper.
- Based on the Taguchi Signal-to-noise ratio analysis the optimum cutting condition for minimum surface roughness and minimum tool wear are cutting (cutting speed v= 105 m/min, feed rate f = 0.112 mm/rev and Depth of cut d= 0.1 mm).
- From the ANOVA it is clear that Feed rate is the most influencing factor for surface roughness obtained by machining with P/M tool with the percentage of 57.27% followed by the cutting speed of 33.9% and depth of cut 8.76%.
- For conventional HSS tool Feed rate is the most influencing factor for surface roughness with the percentage of 72.29% followed by the cutting speed of 30.05% and depth of cut of 61.95%.
- Regression equation were developed surface roughness, obtained by machining copper with P/M tool and HSS tool and it shows the predicted values and the experimental values are in close adhering with each other.
- P/M alloy steel (Fe - 1%C – 2%W – 1%Ti) tool is can be used for copper to get good surface finish.
- Further the alloy of (Fe - 1%C – 2%W – 1%Ti) can be subjected to other hardening process to enhance the strength for machining steels.

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