DEVELOPMENT OF MATHEMATICAL MODEL FOR SURFACE ROUGHNESS AND MATERIAL REMOVAL RATE OF ALUMINIUM ALLOY

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ABSTRACT

Product manufacturers, seeking to remain competitive in the market, rely on their man powers to quickly and effectively set up manufacturing processes for products. Taguchi parameter design is a powerful and well-organized method for optimizing the quality and performance output of manufacturing processes, thus a powerful tool for meeting this challenge. The aim of this research is to use Taguchi parameter design for optimizing the cutting parameters like cutting speed, feed and depth of cut to minimize the surface roughness and to maximize the material removal rate in turning aluminium alloy by conventional lathe. Three types of cutting tools viz. High speed steel (HSS) tool, carbide tool and polycrystalline diamond (PCD) tool were used for turning operations. The experiments were carried out using Taguchi design of experiments with L_{27} orthogonal array. The mathematical model for material removal rate and surface roughness on turning operation was developed using regression analysis. From this research paper, it is found that cutting speed, feed are the most significant parameters and depth of cut is the least significant parameter in favour of surface roughness for all the three cutting tools. Cutting speed, depth of cut are the most significant parameters and feed is the least significant parameter in favour of material removal rate (MRR) for all the three cutting tools.

Keywords*: Surface roughness, Material removal rate, Orthogonal array, Cutting tools, Regression analysis.*

1. Introduction

Surface roughness plays a significant role during machining of any component. The industries productivity and economy increases as they produce the better finished component. A better machined component surface improves the fatigue strength, creep failure, corrosion resistance. In machining, there are number of factors which affect the surface roughness i.e. Cutting parameters, tool variables and work piece variables. Cutting parameters include speed, depth of cut, feed and work piece variable include hardness of material and mechanical properties. In a turning operation, it is very difficult to select the cutting parameters to achieve better surface roughness. Higher material removal rate (MRR) and lower the cutting forces are the needs of industry to cope up with mass production in lesser time. Higher MRR can be achieved by increasing the process parameters such as cutting speed, feed, nose radius and depth of cut. Statistical decision making tool, used to analyze the experimental data and to find any differences in the response means of parameters being tested. It is also needed for estimating the error variance for the parameter effects and variance of the prediction error. In general, the purpose of statistical decision tool is to determine the relative magnitude of the effect of each parameter and to identify the parameter that significantly affects the response under objective function. Regression analysis is used to investigate and model the relationship between a response variable. The dependent variables like surface roughness and material removal rate are conceived as a linear combination of the independent variable namely, cutting speed, feed and depth of cut. The data was analyzed by MINITAB 18 statistical software. After getting the responses for surface roughness and material removal rate, the mathematical models were developed using regression analysis.

1.1 Literature Review

This section covers the published work of researchers pertaining to the turning process in order to optimize the cutting parameters. The scope of the review also extends to various optimization techniques that are used to develop the mathematical model for surface roughness and material removal rate during turning aluminium alloy using regression analysis.

Yogendra Singh Chauhan, performed an experimental study to optimize the cutting parameters viz. nose radius, spindle speed, feed and depth of cut during turning aluminium alloy AA6063-T6 using tungsten carbide insert. The regression analysis was conducted on the tested data to develop the mathematical model to predict the value for surface roughness and material removal rate. [1]

M.Naga Phani Sastry et. al., investigated to determine the process parameters during turning operations (cutting speed, feed and depth of cut) which results in an optimal value of surface roughness and maximum metal removal rate (MRR) during machining aluminium bar with HSS tool. A mathematical model was developed to determine MRR during response surface methodology. [2]

A. Parthiban et. al., have conducted an experimental investigation i.e. the effect of Spindle speed, feed and depth of cut on material removal rate (MRR) and surface roughness during turning AA 6061-T6. To find the improvement in MRR and surface roughness for turning Aluminium alloy AA6061-T6 with respect to the chosen initial parameter setting, confirmation tests were used. The mathematical model was developed to determine MRR and surface roughness by using response surface methodology. [3]

B. Ramreddy et. al., focused on optimizing the process parameters based on the Taguchi method to minimize the surface roughness and maximize the material removal rate of AA7075 with tungsten coated carbide tool. This study revealed that depth of cut has the most influencing effect on the quality attributes of surface roughness than the feed and cutting speed has the most extreme impact on the material removal rate. [4]

B. Radhakrishnan et. al., performed the experiments to optimize the machining parameters to achieve high surface finish. Aluminium 6063 is the work piece material and CCMT cemented carbide tool, the cutting tool is used. Mathematical model was constructed by the response surface methodology (RSM) to fit the relationship between the process parameters and the surface roughness. The prediction accuracy was verified by the one-way analysis of variance. Finally, the surface roughness under different combination of process parameters are obtained and used for the optimum surface roughness prediction. [5]

Pragnesh.R.Patel et. al., have studied the effects of different cutting parameters (cutting Speed, feed, depth of cut) on surface roughness and power consumption in turning of 6063 aluminium alloy TiC (MMCs). Polycrystalline diamond tool was used as wear resistive tool in order to achieve desire surface finish. This study revealed that feed has the most significant parameters which affect the surface roughness. The increase in feed increases the surface roughness. [6]

Puneet Saini et. al., performed the experiments to found, the effect of carbide inserts on EN-24 alloy steel surface by using three parameters (spindle speed, feed and depth of cut). This research was conducted by using 100 HS Stallion CNC lathe machine and the coated tungsten carbide turning insert (CNMG120408).This study revealed that the surface roughness is mainly affected by feed and depth of cut. [7]

Ravi Aryan et. al., [8] performed the experiments using Taguchi method to determine the optimization of cutting parameters for surface roughness, material removal rate in the turning process and to obtain the optimal setting for the process parameters and analysis of variance is used to analyse the influence of cutting parameters during turning Al 6082 alloy.

Ranganath M.S et. al., did experimental work on Al 6061 alloy, the aim is to investigate the effect of the cutting speed, feed rate and depth of cut on surface roughness in CNC turning. The effect of cutting parameters on surface roughness were studied and analysed. The design of experiments was conducted to analyse the influence of the turning parameters on the surface roughness by using Taguchi method and analysis of variance. [9]

From the previous studies, it is observed that most of the work has been done using Taguchi method, analysis of variance (ANOVA) and response surface methodology (RSM) to determine the optimal cutting parameters for surface roughness and material removal rate. They developed the mathematical models using a single tool for surface roughness and material removal rate, but not much work has been done that focuses on three different tools. After reviewing all these papers, it is decided to do the experimental work for surface roughness and material removal rate using three cutting tools viz. HSS tool, carbide tool and PCD tool to turn Al 2014 alloy.

2. Experimental Details

2.1 Test Material

Aluminium 2014 alloy is used for conducting the experiments. It is a high strength material finds applications in aircraft, military vehicles, bridges, weapons manufacture, automotive industry; cylinder, piston and structures.

The composition of Al 2014 alloy is depicted in Table 1.

Table 1: Composition of Al 2014 alloy

Element	**Si**	**Fe**	**Cu**	**Zn**	**Mn**	**Mg**	**Ti**	**Cr**	**Other**	**Al**
Wt.%	0.69	0.25	4.02	0.02	0.65	0.44	<0.02	<0.02	<0.12	Remainder

2.2 Cutting Tools

The turning tools used for this experiment are high speed steel (HSS), carbide and polycrystalline diamond (PCD).

2.3 Process Parameters

The three cutting parameters with three different levels are experimentally constructed for the machining operation. Table 2 indicates the values of process parameters and their levels used for the experiments.

Table 2: Process Parameters and Levels

Cutting Parameters	**Level 1**	**Level 2**	**Level 3**
Cutting Speed(rpm)	384	598	938
Feed Rate(mm/rev)	0.0625	0.125	0.1875
Depth of Cut(mm)	0.2	0.3	0.4

3. Experimental Procedure and Details

Experiments are conducted based on Taguchi's method and as per L_{27} orthogonal array by considering three controllable factors and three levels as shown in Table 2. In the present study, the three different tools are used to turn the Al 2014 alloy material. The experiments were conducted with different tool materials to study the performance characteristics like surface roughness and material removal rate. After each experimental run, the diameter of the work piece and the surface roughness are measured, the Mitutoyo surface roughness tester was used to measure the surface roughness. The considered value for surface roughness (R_a) was taken as the average value from three trials during the experiment. Using average diameter, feed, depth of cut and cutting speed values the material removal rate was calculated using the formula mentioned below:

$$MRR = 3.142 \times D_{avg} \times f \times d \times N \quad mm^3/min$$

Where, D_{avg} = Average diameter between diameter of the work piece before machining and after machining in mm.

f = Feed in mm/rev.

d = Depth of cut in mm.

N = Spindle speed in rpm.

An attempt has been made to assess the factors influencing surface roughness and material removal rate on turning operation. The machining parameters selected for a turning operation is an important procedure in order to achieve high performance. So the best parameter is to judge the quality of turned product is surface roughness which is very important for product. The attempt made here to minimize the surface roughness, to maximize the material removal rate and to accomplish towards the optimal parameters by optimizing some of the cutting parameters viz. cutting speed, feed and depth of cut. The experiments were carried out using a systematic procedure of Taguchi parameter. At first the design of experiment has to be implemented to select cutting speed, feed and depth of cut that could result in a better quality product. The response table and response graph for each level of machining parameters are obtained from the Taguchi method and the optimum levels of machining parameters are being selected.

The aim of this study is to determine the process parameters which maximize the material removal rate and to achieve minimum surface roughness. Larger-the-better quality characteristic is used for material removal rate, as the larger material removal rate value represent better. Smaller-the-better quality characteristic is used for surface roughness, as the smaller surface roughness value represent improved or better productivity. MINITAB 18 Software was used to investigate which design factor and their interactions affect the response considerably. The response data was obtained through experimental runs for surface roughness and MRR are at above 95% confidence level. Regression analysis is used to develop the mathematical model for surface roughness and material removal rate.

4. Results and Discussions

4.1 Regression Analysis for Surface Roughness

From the Table 3, it is observed that the surface roughness was most influenced by cutting speed, feed and the interaction effect of cutting speed and feed. The other interactions of design parameters and depth of cut do not have major influence on surface roughness. In statistical analysis of Taguchi method, the smallest P value gives more significant effect on responded surface roughness parameters.

Table 3: Coefficients table for HSS Tool

Term	Coef	SE Coef	T-Value	P-Value
Constant	-0.411	0.702	-0.59	0.565
Cutting Speed (v)	-0.642	0.131	-4.90	0.000
Feed (f)	1.763	0.131	13.44	0.000
Depth of Cut (d)	0.133	0.131	1.01	0.325
v*f	0.285	0.131	2.17	0.043
v*d	0.032	0.131	0.25	0.807
f*d	-0.078	0.131	-0.59	0.560
v*f*d	-0.012	0.131	-0.09	0.928

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.556513	91.73%	88.69%	83.68%

The Regression equation obtained for surface roughness as shown in equation (1).

$\mathbf{R_a}$ = -0.411-0.642*v + 1.76*f + 0.133*d + 0.285*v*f + 0.032*v*d – 0.078*f*d – 0.012*v*f*d .... equation (1)

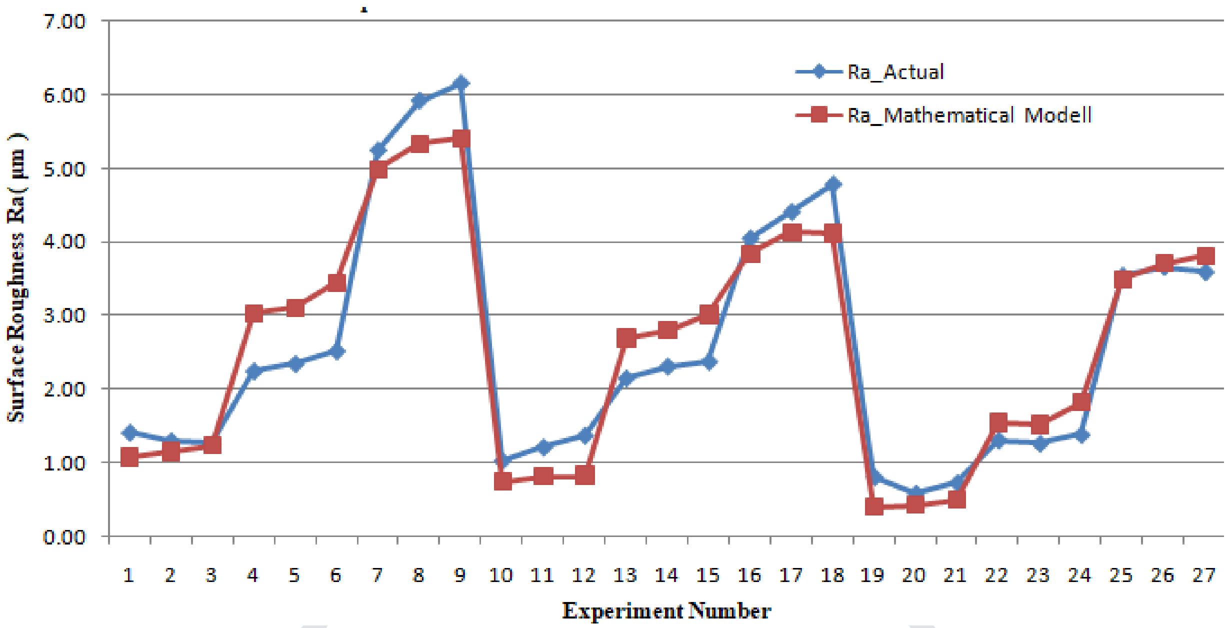

Fig. 1 Comparison between Actual R_a and Mathematical model R_a for HSS Tool

From the Table 4, it is observed that the surface roughness was most influenced by feed, depth of cut and the interaction effect of cutting speed and feed. The other interactions of design parameters and cutting speed do not have major influence on surface roughness. In statistical analysis of Taguchi method, the smallest P value gives more significant effect on responded surface roughness parameters.

Table 4: Coefficients table for Carbide Tool

Term	Coef	SE Coef	T-Value	P-Value
Constant	-1.627	0.431	-3.78	0.001
Cutting Speed (v)	-0.0894	0.0804	-1.11	0.280
Feed (f)	1.8444	0.0804	22.94	0.000
Depth of Cut (d)	0.3608	0.0804	4.49	0.000
v*f	0.3692	0.0804	4.59	0.000
v*d	0.0522	0.0804	0.65	0.524
f*d	0.0769	0.0804	0.96	0.351
v*f*d	0.1008	0.0804	1.25	0.225

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.341164	96.78%	95.60%	93.40%

The Regression equation obtained for surface roughness as shown in equation (2).

$$\mathbf{R_a} = -1.62 - 0.0894*v + 1.84*f + 0.36*d + 0.37*v*f + 0.052*v*d + 0.077*f*d + 0.10*v*f*d \quad .....\text{equation (2)}$$

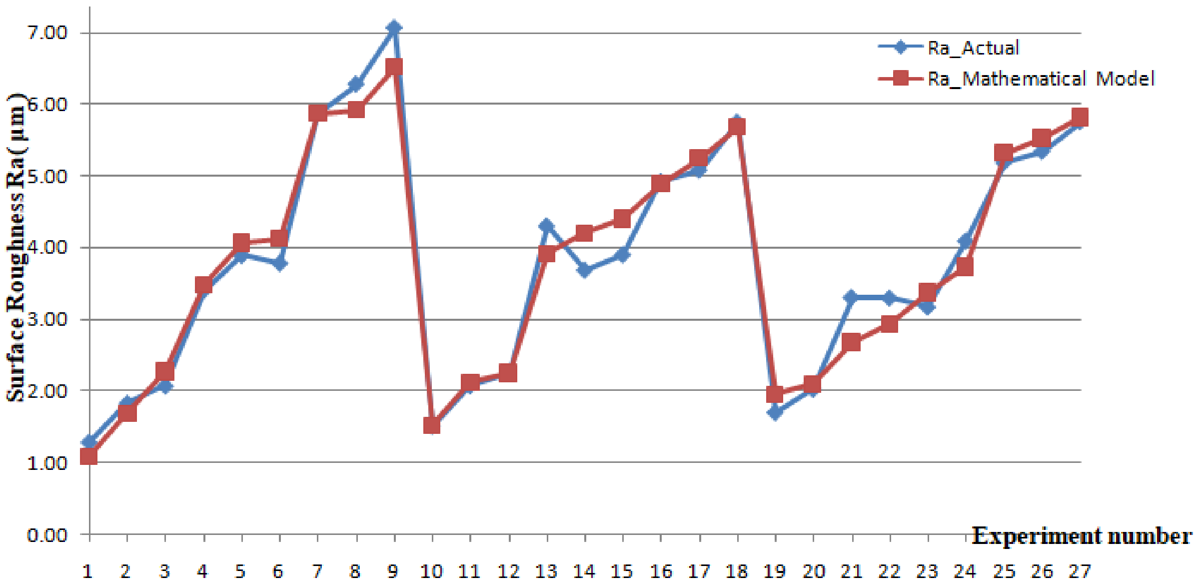

Fig. 2 Comparison between Actual R_a and Mathematical model R_a for Carbide Tool

From the Table 5, it is observed that the surface roughness was most influenced by cutting speed, feed and the interaction effect of cutting speed and feed. The other interactions of design parameters and depth of cut do not have major influence on surface roughness. In statistical analysis of Taguchi method, the smallest P value gives more significant effect on responded surface roughness parameters.

Table 5: Coefficients table for PCD Tool

Term	Coef	SE Coef	T-Value	P-Value
Constant	-3.52	2.45	-1.44	0.167
Cutting Speed (v)	2.160	0.458	4.72	0.000
Feed (f)	2.667	0.458	5.83	0.000
Depth of Cut (d)	0.211	0.458	0.46	0.650
v*f	-1.222	0.458	-2.67	0.015
v*d	-0.138	0.458	-0.30	0.767
f*d	0.162	0.458	0.35	0.728
v*f*d	-0.131	0.458	-0.29	0.778

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.94105	77.09%	68.64%	53.74%

The Regression equation obtained for surface roughness as shown in equation (3).

$\mathbf{R_a}$ = - 3.52 + 2.160*v + 2.667*f + 0.211*d – 1.22*v*f – 0.138*v*d + 0.162*f*d – 0.131*v*f*d ......equation (3)

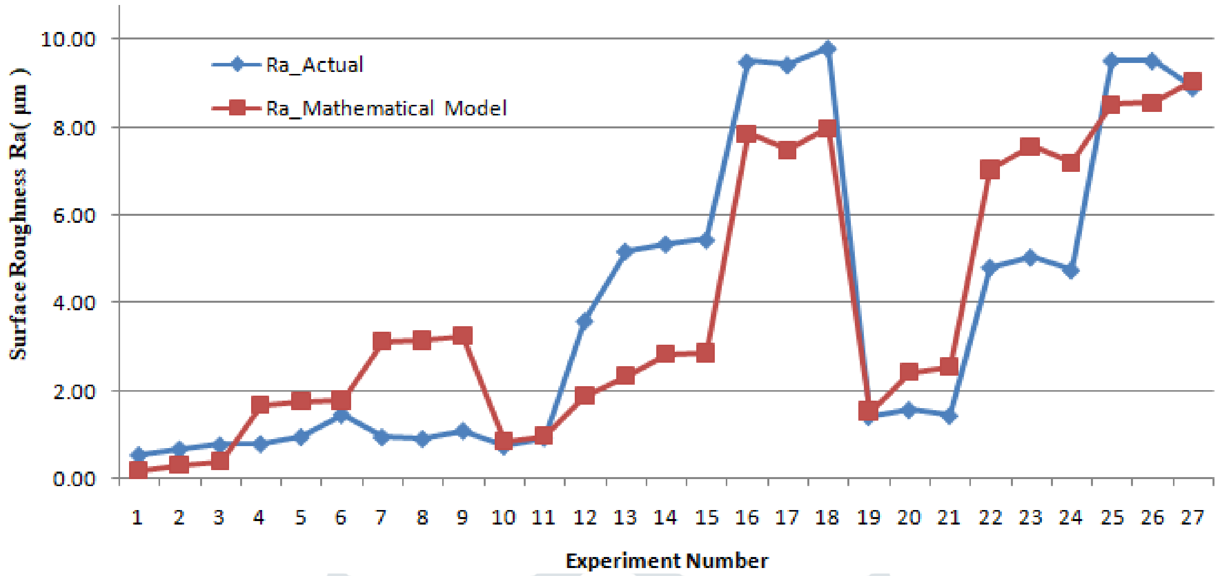

Fig. 3 Comparison between Actual R_a and Mathematical model R_a for PCD Tool

From equation 1, equation 2 and equation 3, it is concluded that, the increase in cutting speed value minimize the surface roughness value, so that the cutting speed plays a negative impact on surface roughness. The increase in feed and depth of cut values maximize the surface roughness value, so that both the feed and depth of cut plays a positive impact on surface roughness. If R-sq(pred) value from the model summary table is close to 100%, then it tells that the equation obtained will fit to get the optimum result during turning operation.

Fig. 1, Fig. 2 and Fig. 3**,** provides the comparision between the actual surface roughness and the mathematical model surface roughness for all three cutting tools viz. carbide tool, HSS tool and PCD tool. From that graphs it evidently concluded that carbide tool has less variation between two surface roughnesses than the HSS and PCD tools.

4.2 Regression Analysis for Material Removal Rate

From the Table 6, it is observed that the material removal rate was most influenced by cutting speed, feed, depth of cut and the interaction effect of cutting speed and feed. The other interactions of design parameters do not have major influence on material removal rate. In statistical analysis of Taguchi method, the smallest P value gives more significant effect on responded material removal rate parameters.

Table 6: Coefficients table for HSS Tool

Term	Coef	SE Coef	T-Value	P-Value
Constant	-2621	673	-3.90	0.001
Cutting Speed (v)	1194	126	9.50	0.000
Feed (f)	1230	126	9.80	0.000
Depth of Cut (d)	858	126	6.83	0.000
v*f	-258	126	-2.05	0.054
v*d	-176	126	-1.40	0.177
f*d	-199	126	-1.58	0.130
v*f*d	24	126	0.19	0.850

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
532.897	92.71%	90.03%	85.66%

The Regression equation obtained for MRR as shown in equation (4).

MRR = -2621 + 1194*v + 1230*f + 858*d - 258*v*f - 176*v*d - 199*f*d + 24*v*f*d ....equation (4)

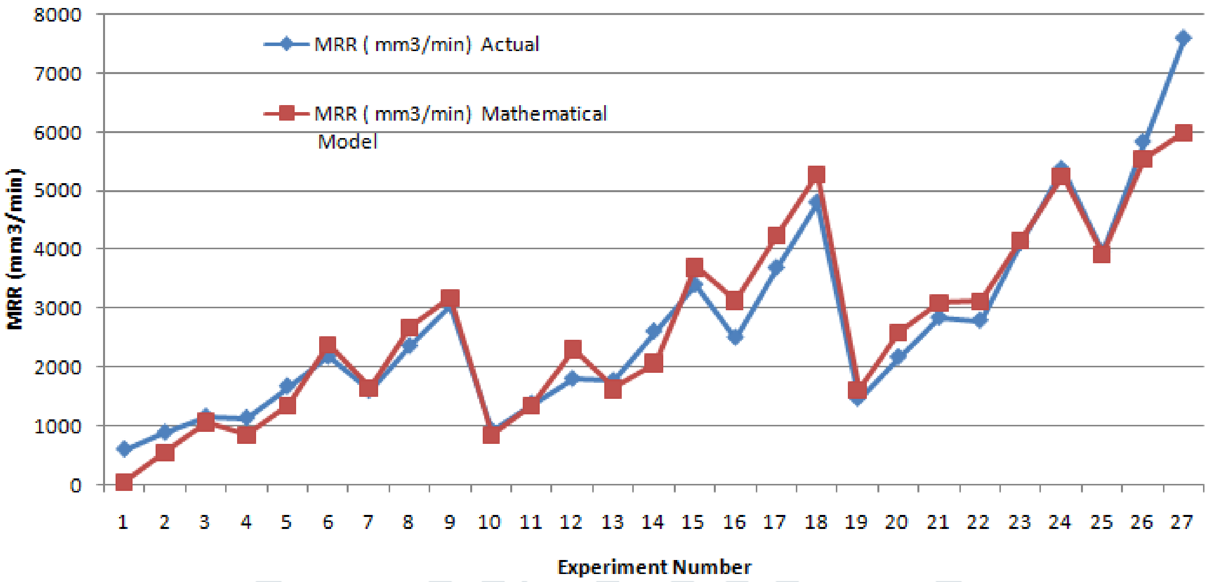

Fig. 4 Comparison between Actual MRR and Mathematical Model MRR for HSS Tool

From the Table 7, it is observed that the material removal rate was most influenced by cutting speed, feed, depth of cut and the interaction effect of cutting speed and feed. The other interactions of design parameters do not have major influence on material removal rate. In statistical analysis of Taguchi method, the smallest P value gives more significant effect on responded material removal rate parameters.

Table 7: Coefficients table for Carbide Tool

Term	Coef	SE Coef	T-Value	P-Value
Constant	-2121	492	-4.32	0.000
Cutting Speed (v)	864.5	91.8	9.42	0.000
Feed (f)	1173.4	91.8	12.78	0.000
Depth of Cut (d)	776.6	91.8	8.46	0.000
v*f	-206.5	91.8	-2.25	0.037
v*d	-139.9	91.8	-1.52	0.144
f*d	-193.2	91.8	-2.10	0.049
v*f*d	30.3	91.8	0.33	0.745

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
389.491	94.64%	92.67%	89.38%

The Regression equation obtained for MRR as shown equation (5).

MRR = -2121 + 865*v + 1173*f +776.6*d - 206.5*v*f – 140*v*d – 193*f*d + 30.3*v*f*d ....equation (5)

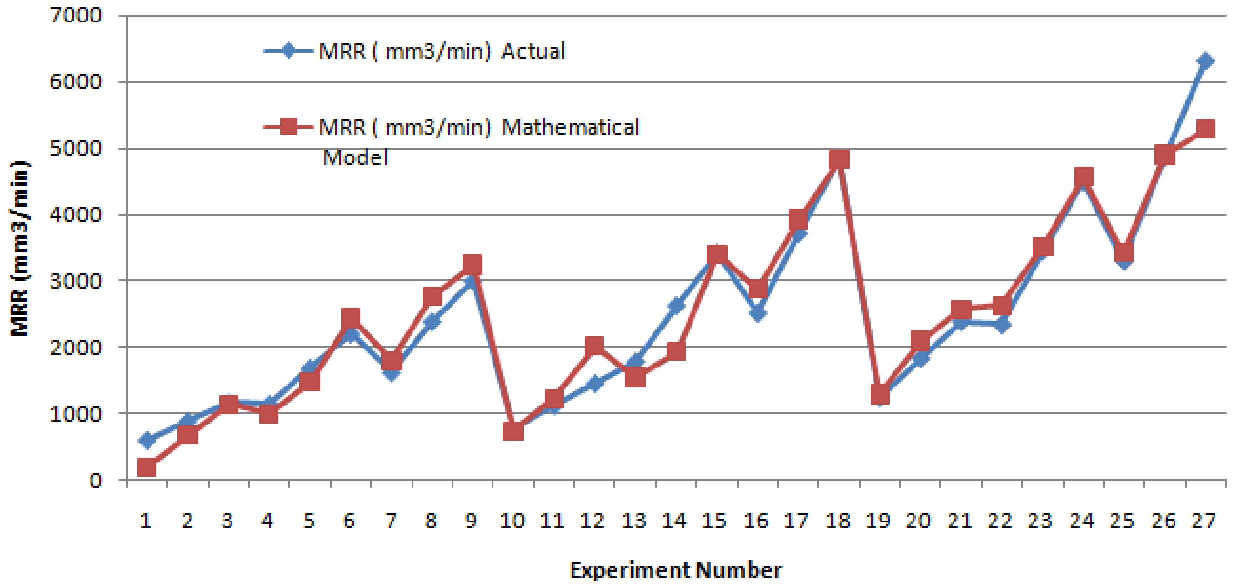

Fig. 5 Comparison between Actual MRR and Mathematical Model MRR for Carbide Tool

From the Table 8, it is observed that the material removal rate was most influenced by cutting speed, feed, depth of cut and the interaction effect of cutting speed and feed. The other interactions of design parameters do not have major influence on material removal rate. In statistical analysis of Taguchi method, the smallest P value gives more significant effect on responded material removal rate parameters.

Table 8: Coefficients table for PCD Tool

Term	Coef	SE Coef	T-Value	P-Value
Constant	-2585	645	-4.01	0.001
Cutting Speed (v)	1160	120	9.63	0.000
Feed (f)	1232	120	10.23	0.000
Depth of Cut (d)	859	120	7.13	0.000
v*f	-249	120	-2.06	0.053
v*d	-172	120	-1.43	0.169
f*d	-200	120	-1.66	0.113
v*f*d	25	120	0.20	0.841

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
510.893	93.12%	90.59%	86.48%

The Regression equation obtained for MRR as shown in equation (6).

MRR = -2585 + 1160*v + 1232*f +859*d - 249*v*f – 172*v*d – 200*f*d + 25*v*f*d ....equation (6)

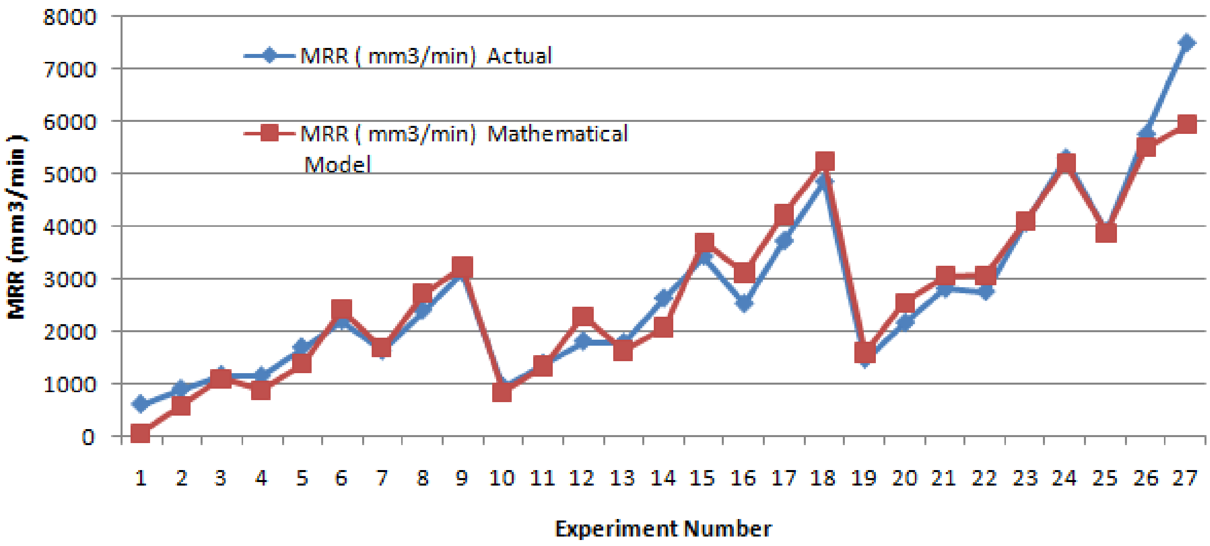

Fig. 6 Comparison between Actual MRR and Mathematical Model MRR for PCD Tool

From equation 4, equation 5 and equation 6, it is concluded that, increase in all the cutting parameters viz. cutting speed, feed and depth of cut values maximize the material removal rate value, so that all the cutting parameters plays a positive impact on the material removal rate. If R-sq(pred) value from the model summary table is close to 100%, then it tells that the equation obtained will fit to get the optimum result during turning operation.

Fig. 4, Fig. 5 and Fig. 6**,** provides the comparision between the Actual MRR and the mathematical model MRR for all three cutting tools viz. carbide tool, HSS tool and PCD tool. From that graphs it clearly concluded HSS tool has less variation between two MRRs than the carbide and PCD tools.

5. Conclusions

This research presented an experimentation approach to study the effect of input parameters on the surface roughness and MRR in turning Al 2014 alloy. The following conclusions were drawn on the experimental investigations:

The main objective is to develop the statistical model using regression analysis.

From regression analysis, it can be concluded that feed has the most influencing effect on the quality characteristics of surface roughness and cutting speed, feed and depth of cut are the most influencing effects on the quality characteristics of material removal rate. Optimum parameter setting for surface roughness and material removal rate in turning is obtained

The optimum parameters obtained for surface roughness are shown given below, that are smaller deviation from experimental (Actual) data.

For HSS Tool: v = 938 rpm, f = 0.0625 mm/rev and d = 0.3 mm.

For Carbide Tool: v = 938 rpm, f = 0.0625 mm/rev and d = 0.3 mm.

For PCD Tool: v = 598 rpm, f = 0.0625 mm/rev and d = 0.3 mm.

The optimum parameters obtained for material removal rate are shown given below, that are smaller deviation from experimental (Actual) data.

For HSS Tool: v = 938 rpm, f = 0.125 mm/rev and d = 0.3 mm.

For Carbide Tool: v = 938 rpm, f = 0.1875 mm/rev and d = 0.3 mm.

For PCD Tool: v = 938 rpm, f = 0.1875 mm/rev and d = 0.2 mm.

This study confirms that the developed model can be used to predict the material removal rate and surface roughness value in an effective manner. The statistical model for predicting the values of surface roughness and material removal rate is developed successfully. Also the interaction effects of various parameters on the output variables were studied.

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