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Experimental investigation of machining characteristics in turning of DELRIN

Ankit Kumar[1], Munish Mehta[2] and Ravinder Kataria[3]

[1, 2] HCTM Technical Campus, Kaithal (Haryana), India

[3]Lovely Professional University, Phagwara, (Punjab) India

Abstract

Turning is one the most important machining operation in industries. The process of turning is influenced by many factors such as the cutting speed, feed rate, depth of cut, geometry of cutting tool cutting conditions etc. The finished product with desired attributes of size, shape, and surface roughness and cutting forces developed are functions of these input parameters. Properties wear resistance, fatigue strength, coefficient of friction, lubrication, wear rate and corrosion resistance of the machined parts are greatly influenced by surface roughness.
The objective is to evaluate the optimal setting of cutting parameters speed, depth of cut, feed to have a maximum material removal rate (MRR) and minimum surface roughness. For this investigation, thermoplastic polymer polyoxymethylene (commercial name - delrin) is used as work piece and high speed steel (HSS) as tool. The design of experiment is based on Taguchi L9 orthogonal array. Further, the analysis of variance (ANOVA) is used to analyze the results obtained from Taguchi design technique.
Keywords: Delrin, Taguchi, S/N ratio, ANOVA, DOE.

1. Introduction

Turning is an operation of removing excess amount of material from the surface (cylindrical or circumference) of the cylindrical work piece. This operation is done to reduce the diameter of the work piece. The part is rotated while a single point cutting tool is moved parallel to the axis of rotation. Turning can be done on the external surface of the part as well as internally (boring). The job to be machined is fixed and rotated in a lathe chuck, a cutting tool is loaded which is stationary against the rotating job. Since the cutting tool material is harder than the work piece, so metal is easily removed from the job.The cutting tool material may be HSS, carbon steels, carbide coated inserts, cast cobalt alloys, cermets, ceramics and diamond. Sometimes cutting fluid or coolant is also used for smooth cutting which includes water, oils, oil-water emulsions, pastes, gels etc. which improves the tool life and finishing of the work piece. Materials which can be turned are metals, alloys, cast iron, stainless steel, carbon steels, thermoplastics etc. Turning is used to produce rotational, typically axissymmetric, parts that have many features, such as holes, grooves, threads, tapers, various diameter steps, and even contoured surfaces.

2. Literature survey

Poornima and Sukumar (2012) represented the experimental study to identify the optimized parameters for surface roughness using RSM and genetic algorithm. Martensitic stainless steel was chosen as the work material. The impact of the machining parameters speed, feed and depth of cut on surface roughness has been investigated. The results obtained from RSM was 99.9% which indicates that selected parameters significantly affect the surface roughness. **Davis et al. (2012)** worked on EN24 steel using L9 orthogonal array with output parameter surface roughness under the dry environment. Spindle speed, feed and depth of cut were taken as the process parameters and carbide cutting tool was employed for turning of EN 24 steel. S/N ratio and ANOVA were employed to study the various performance characteristics. Feed was found as the most significant factor which affects surface roughness.

Abhang and Hameedullah (2012) found the effect of lubricant temperature on surface finish. EN 31 steel alloy was turned using diamond shape carbide insert by selecting feed rate, depth of cut and lubricant temperature as the process parameters. Taguchi's L9 orthogonal array was used to design the experiments. The study reveals that lubricant temperature and feed rate are the main parameters that influence surface finish. Better surface finished is obtained by applying cooled lubricant. Even with high depth of cut surface finish was improved if lubricant temperature was lowered. **Makadia and Nanavati (2012)** used AISI 410 steel to study the effect of various machining parameters on surface roughness using RSM. Three level experiments were conducted by using four parameters namely cutting speed, feed, depth of cut and tool nose radius which means a total of 81 experiments were conducted. The study revealed that feed rate is the main influencing factor on the roughness which was followed by the tool nose radius and cutting speed while depth of cut had no significant effect on the surface roughness. **Das et al. (2012)** worked on AISI D2 steel to represent the impact of cutting parameters depth of cut, feed and cutting speed to achieve the minimum tool wear and low work piece surface temperature by using coated carbide insert under dry conditions. Surface temperature flank wear was measured using infrared thermometer and profile projector respectively. Outcomes showed that the percent contribution of depth of cut and cutting speed in affecting the variation of tool wear were significantly larger as compared to the contribution of the feed. Cutting speed and depth of cut were the significant factor for work piece surface temperature.

Magdum and Naik (2013) investigated the use of tool materials and process parametersto find out the thrust force and feed force. The selected parameters were cutting speed, depth of cut, feed and tool shape of material. Three types of tool materials i.e. HSS, carbide and cermet were used in this investigation. A total of 9 experiments were conducted on EN 8 steel. Results of cutting experiments were studied by using S/N ratio and ANOVA. Based on these results optimal cutting parameters for cutting force are obtained. **Prasad D.V.V.K. (2013)** studied the influence of three machining parameters (cutting speed, feed and depth of cut) and two tool geometrical parameters (back rake angle and side rake angle) on surface roughness of mild steel. A total of 243 experiments were conducted on 41 pieces. After finalizing the results, it was concluded that feed is significant factor influencing surface roughness and side rake angle has very less effect on the surface roughness. **Lavanya et al. (2013)** carried out finished turning of AISI 1016 suing CBN insert tool to predict the surface roughness. For prediction of surface roughness, artificial neural network models were developed. Neural network based predictions of surface roughness compared with experimental data and the results thereof showed that proposed neural network models were efficient to predict surface roughness patterns for a range of cutting conditions. From the multiple linear regression analysis, the interaction terms of speed, feed and depth of cut are not significant on the surface roughness. From the sensitivity analysis, feed is the most influenced cutting parameter on the surface roughness followed by speed and depth of cut.

Kondekar et al. (2013) presented the work to predict the influence of cutting speed, feed, depth of cut and various insert materials in dry or wet condition on surface roughness using DOE and statistical techniques for AISI D2 metal matrix composite. Coated CBN was used as machine tool while cutting speed, feed, depth of cut and machining time were taken as process parameters. Experiments were performed in the wet environment.**Bhuiyan and Ahmed (2014)** discussed the development of a cutting force prediction system for turning operation, using RSM and GA. The experiments were designed using various operating parameters like cutting speed, feed rate and depth of cut. These operating parameters were predominately used in carrying out experiments. 16 experiments were conducted using uncoated carbide insert as machine tool under dry conditions for turning of AISI 1040 steel. A model for calculating cutting force was developed. By using this model, value of cutting force can be predicted for a given set of cutting speed and feed rate.

Jachak and Pandey (2014) worked on the medium carbon steel AISI 1055 by using adhesive bonded carbide insert tool. Factorial experimentation technique was used to study the effect of various process parameters depth of cut, cutting speed and feed on surface roughness. Factorial experimentation helped in finalizing the number of levels for experimentation and thus no. of experiments has been finalized. A total of 16 experiments were performed. As a result, adhesive bonded tool can be used for optimizing the turning process parameters for minimizing the surface roughness and maximize the tool life by experimental setup. **Jadhav and Jadhav (2014)** worked to represent the impact of cutting parameters (cutting speed, feed and depth of cut) on cutting force and feed force. Taguchi design method was used to predict the no. of experiments. 27 experiments and 2 replicates were carried out by using HSS tool. It is observed that the feed rate has significant influence on both the cutting force and surface roughness. Cutting Speed has no significant effect on the cutting force as well as the surface roughness of the chosen work piece. Depth of cut has a significant influence on cutting force, but an insignificant influence on surface roughness.

Davis et al. (2014) reported the optimization of the multiple machine characteristics (depth of cut, feed rate and spindle speed) in turning of EN 24 steel by using carbide P 30 cutting tool under wet condition. The single optimization was conduct by Taguchi method. ANOVA was used to find out the most influential parametric combination. ANOVA showed that all of the factors are insignificant. **Acharya and Karwande (2014)** worked on EN 31 steel using RSM taking 5 parameters namely cutting speed, feed rate, depth of cut, wet & MQL system and insert nose radius. Area of interest were surface roughness, MRR, machining time and comparing wet & MQL system. Various types of CBN inserts were employed to machine the work piece. It has been concluded from the study feed rate has significant effect on surface roughness, depth of cut was the major parameter to control tool wear. MQL system was found to be better than wet lubrication system.

Kataria and Kumar (2014) paper explained the turning operation for AISI O1 tool steel. Taguchi method, weighted S/N Ratio, grey relational analysis, Utility Concept and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods were used to optimize the MRR) and surface roughness responses collectively. The experimental results shows that there has been considerable difference among the optimal settings yielded by the methods investigated. **Sahu and Maity (2015)** worked to study how output parameters like cutting force, surface roughness and tool wear related to the input parameters. Austenitic steel of AISI 202 grade and uncoated carbide insert were taken as the work piece and cutting tool respectively under dry conditions. RSM and ANOVA were used to study the effect of input parameters (cutting speed, feed and depth of cut) which further revealed that speed is the most significant factor affecting cutting force, feed is the most significant factor on surface roughness and depth of cut is most influential parameter for tool wear. **Lakshmi et al. (2015)** discussed an application of the regression analysis for optimizing the cutting parameters in turning operation of aluminium 7075 alloy using tungsten carbide cutting tool. In this study regression analysis provides a systematic and efficient methodology for the optimization of the cutting parameters with far less effect than would require for most optimization techniques. The tool traverse feed observed to have more influence on the mean of surface finish and mean of MRR as compared to cutting speed and depth of cut.

Das et al. (2016) used Taguchi approach, regression analysis and ANOVA to investigate the effect of input parameters on surface roughness, tool wear, power consumption and chip reduction coefficient. Uncoated carbide insert under dry conditions was used for turning of chrome moly alloy steel. 27 experiments were conducted which revealed that feed rate is significant only in case of surface roughness while it has no effect on other output parameters. Speed was the most significant parameter for power consumption and flank wear. It had negligible effect on surface roughness and chip reduction coefficient. Depth of cut is found to be more significant in case of chip reduction coefficient but less effective on other parameters. **Alagarsamy et al. (2016)** made an attempt to investigate the effect of cutting parameters (speed, feed and depth of cut) to get higher MRR and less machine time in hard turning of aluminium alloy 7075 using tungsten carbide insert as cutting tool. Taguchi method was employed to design experiments. A total of experiments were conducted which explained that cutting speed was more significant factor influencing MRR followed by feed rate. Depth is cut was the least significant factor. ANOVA for machining time indicated that the cutting speed is major contributor in obtaining optimal surface roughness followed by feed rate and depth of cut. **Puh et al. (2016)** have studied about dependence of surface roughness and MRR on cutting speed, feed rate and depth of cut. Carbon steel bar was turned by using coated insert under dry cutting conditions. Grey relational analysis technique for the experimentation. Cutting speed and depth of cut were two parameters significantly influencing the grey relational grade. And the depth of cut was the most effective factor.

Naik et al. (2016) committed an investigation of turning of AISI 410 stainless steel using HSS tool. Taguchi method was used to design the experiments for finding the optimum parameters for smooth surface. L9 orthogonal array was selected based on which 9 experiments were done at 3 levels. Outcome showed that feed was the most influencing parameter corresponding to the quality characteristics of surface roughness. **Upletawala and Katratwar (2016)** worked on the thermoplastic polymer Delrin 500 AL to represent the impact of cutting parameters speed, feed and depth of cut on MRR and surface roughness. Taguchi method was used to predict the no. of experiments to be done. L9 orthogonal array, S/N ratio and ANOVA were used to investigate the cutting characteristics of delrin using HSS tool. The study revealed that the dominating factor affecting the surface roughness is feed, followed by speed. Material removal rate is dominantly affected by depth of cut. **Telrandhe et al. (2016)** attempted to discuss the effect of microstructure on machinability of Ti_6Al_4Valloy at different cutting speed while keeping feed rate and depth of cut constant under dry environment. Carbide insert tool was used to machine the work piece. It was concluded that hardness and degree of misorientation decreases with annealing and grain growth was observed for the samples annealed at a higher temperature. Depth of deformation zone and misorientation were reduced with increase in cutting speed.

3. Experimental Setup and Methods

A. CNC MACHINE

HAAS CNC lathe machine was used for the experimentation. The size and the shape of the work piece were selected based on the availability from the supplier. Also the work piece design was finalized keeping in the view the capabilities of the machine to ensure the better performance in machining the work piece. HAAS CNC lathe machine is shown in fig. 1 and the specifications of the machine are shown in table 1.

B. CUTTING TOOL MATERIAL

HSS tool is used for the experimentation is shown in fig. 2. It has high working efficiency, can be reused, save cost, long service life and has excellent accuracy of positioning.

Table 1 Machine Specifications

Power Supply	**AC 415 V**
Operating Frequency	50 Hz
Control Voltage	195-260 V
Maximum Spindle Speed	1800 rpm
Depth of Cut	0.2-4.8 mm
Maximum Feed	11.4 m/min

Fig. 1 HAAS CNC Lathe Machine

Fig. 2HSS Tool

C. WORK MATERIAL

Table 2 Work Piece Specifications

Work Piece Specifications	
Work piece material	Delrin
Work piece size	Length = 300 mm, Diameter = 40 mm
Sample size	20 mm
Shape	Cylindrical

Fig. 3 Work Piece (After Turning)

Polyoxymethylene (POM), also known as acetal, polyacetal and polyformaldehyde, is an engineering thermoplastic used in precision parts requiring high stiffness, low friction, and excellent dimensional stability. Its chemical formula is $(CH_2O)_n$. Delrin is intrinsically opaque white, due to its high crystalline composition, but it is available in all colors. Typical applications for injection-molded delrin include high-performance engineering components such as small gear wheels, eyeglass frames, ball bearings, ski bindings, fasteners, guns, knife handles, and lock systems. The material is widely used in the automotive and consumer electronics industry. Work piece specifications are shown in table 2 and work material (after turning) is shown in fig. 3.

D. FACTORS AND LEVELS

After conducting the literature survey it has been seen that three factors speed, feed and depth of cut are mostly selected. Also 3 levels of each factor is considered. The values for different factors and levels are taken with consideration from the expertise of people working on CNC or lathe machine. The values are equally spaced. Table 3 shows the factors along with the level values.

Table 3 Factors and their Levels

S. No.	Factor	Level 1	Level 2	Level 3	Unit
1	Spindle Speed (A)	400	800	1200	rpm
2	Feed (B)	0.3	0.5	0.7	mm/rev
3	Depth of Cut (C)	0.25	0.50	0.75	mm

E. SELECTION OF ORTHOGONAL ARRAY

Table 4 shows the control log for experimentation.

Table 4 Control Log for Experimentation

Ex. No.	A	B	C	Spindle Speed (rpm)	Feed (mm/rev)	Depth of Cut (mm)
1	1	1	1	400	0.3	0.25
2	1	2	2	400	0.5	0.50
3	1	3	3	400	0.7	0.75
4	2	1	2	800	0.3	0.50
5	2	2	3	800	.0.5	0.75
6	2	3	1	800	0.7	0.25
7	3	1	3	1200	0.3	0.75
8	3	2	1	1200	0.5	0.25
9	3	3	2	1200	0.7	0.50

The spindle speed, feed and depth of cut has three levels. In present case according to above two conditions mentioned L9 Array was selected for this study. As no interaction was of interest so from standard array, only first three columns have been used. The standard L9 orthogonal array has been shown in table 4.6. For present investigation each of input parameters i.e. spindle speed, feed and depth of cut, total degree of freedom are

Total degree of freedom = 2 × 3 = 6

Hence L9 orthogonal array (having 8 degree of freedom) can be adopted for planning of experimentation, based on computation of degree of freedom.

4. Results and Discussion

A. COMPUTATION OF MRR

MRR is calculated as, $\mathrm{MRR} = \pi \times D_{avg} \times d \times f \times N$

Where, $D_{avg} = \frac{D_i + D_f}{2}$

D_{avg} = Average diameter,

d = Depth of cut,f = Feed, N = Speed

B. SURFACE ROUGHNESS

After conducting the experiment, Surface roughness is measured by a surface tester instrument calledZeiss AccretechSurfcom Flex 50A. It gives the value of different roughness parameters i.e. R_a, R_z and R_q. We are concentrating on value of R_a that is basically average surface roughness.

C. S/N RATIO

We have to maximize the Material Removal Rate; Larger-the-better type of S/N ratio is selected.
S/N ratio (ɳ) = -10 log [$1/ny^2$], where n=1
We have to minimize the Surface roughness; Smaller-the-better type of S/N ratio is selected.
S/N ratio (ɳ) = -10 log [ny^2], where n=1

Table 5 Observation Table

Ex. No.	Spindle Speed	Feed	Depth of Cut	MRR (Mean)	S/N Ratio for MRR (dB)	R_a (Mean)	S/N Ratio for Ra (dB)
1	400	0.3	0.25	3261.672	70.2688	3.511	-10.9086
2	400	0.5	0.50	10990	80.8200	3.876	-11.7677
3	400	0.7	0.75	23491.122	87.4181	4.476	-13.0178
4	800	0.3	0.50	13659	82.7084	3.652	-11.0339
5	800	0.5	0.75	34736.25	90.8157	4.005	-12.0521
6	800	0.7	0.25	15880.55	84.0173	4.397	-12.8631
7	1200	0.3	0.75	31262.62	89.9005	3.422	-10.6856
8	1200	0.5	0.25	17603.62	84.9120	3.542	-10.9850
9	1200	0.7	0.50	49784.7	93.9419	3.753	-11.4876

D. MAIN EFFECTS PLOT

The main effect plot of raw data and those of S/N ratios for response variables are shown in fig. 4 and 5.

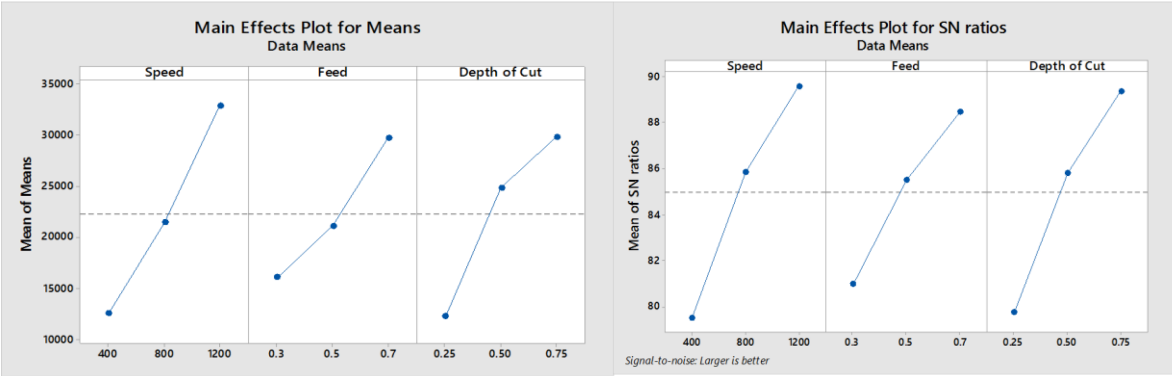

Fig. 4 Effect of Process Parameters on MRR – Raw Data and S/N Ratios

From the graph, the optimum combination for MRR obtained is A3B3C3.

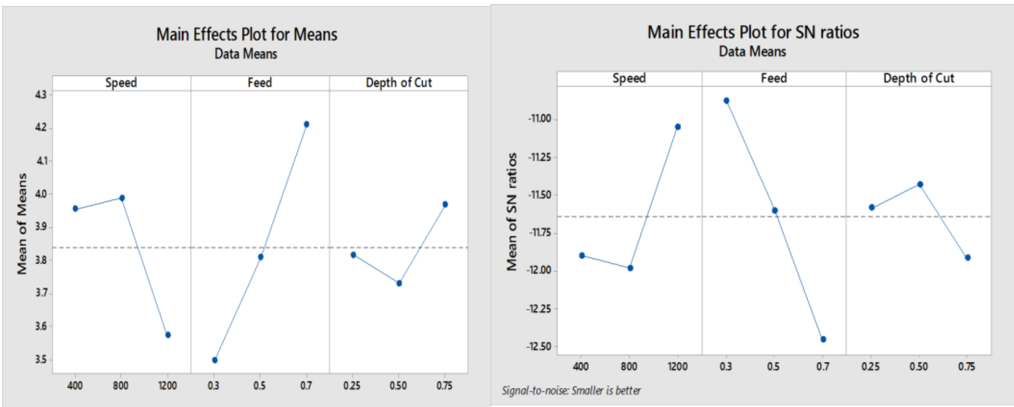

Fig. 5 Effect of Process Parameters on Surface Roughness – Raw Data and S/N Ratios

From the graph, the optimum combination for surface roughness obtained is A3B1C2.

E. ANALYSIS OF VARIANCE (ANOVA)

Table 6 ANOVA for MRR (Raw Data)

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Speed	2	621716990	310858495	2.82	0.262	38.37
Feed	2	286135591	143067795	1.30	0.435	17.66
Depth of Cut	2	492112437	246056218	2.24	0.309	30.37
Error	2	220157495	110078747			
Total	8	1620122511				

S = 10491.8, R-sq = 86.41%, R-sq (adj) = 45.64%, R-sq (pred) = 0.00%

ANOVA is a statistical method used to interpret experimental data and make the necessary decision. ANOVA (general linear model) for mean value has been performed to identify the significant parameters to quantify their effect on the performance characteristics. The ANOVA test for the data is given in the tables 6 to table 9.

Table 7ANOVAfor MRR (S/N Ratio)

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Speed	2	155.885	77.9425	8068.79	0.000	40.55
Feed	2	85.674	42.8368	4434.57	0.000	22.29
Depth of Cut	2	142.765	71.3826	7389.69	0.000	37.14
Error	2	0.019	0.0097			
Total	8	384.343				

S =0.0982840, R-sq = 99.99%, R-sq (adj) = 99.98%, R-sq (pred) = 99.90%

Table 8ANOVA for Surface Roughness (Raw Data)

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Speed	2	0.3198	0.15992	9.88	0.092	26.65
Feed	2	0.7610	0.3805	23.5	0.041	63.42
Depth of Cut	2	0.0865	0.0432	2.67	0.272	7.20
Error	2	0.0323	0.016			
Total	8	1.1998				

S = 0.127240, R-sq = 97.30% , R-sq (adj) = 89.21%, R-sq (pred) = 45.35%

Table 9ANOVA for Surface Roughness (S/N Ratio)

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Speed	2	1.5873	0.7936	12.12	0.076	27.15
Feed	2	3.7536	1.8767	28.67	0.034	64.21
Depth of Cut	2	0.3740	0.1870	2.86	0.259	6.39
Error	2	0.1309	0.0654			
Total	8	5.8458				

S = 0.255843, R-sq = 97.76% , R-sq (adj) = 91.04%, R-sq (pred) = 54.65%

5. Conclusion

In this thesis, the Taguchi method is used for finding the optimum parameters for material removal rate and surface roughness in turning operation of delrin. Three factors i.e. speed, feed and depth of cut along with three levels of each factor were considered. By obtaining the result of S/N ratios, graphs and ANNOVA, following conclusions are given;

1. A Taguchi design technique is one of the latest optimization techniques which is used in industries for optimum selection of levels of various variables and increasing the profit by increasing the quality and productivity.
2. The optimum cutting parameter for Material Removal Rate is obtained at combination of A3B3C3 i.e. speed at level 3 - 1200 rpm, feed at level 3 - 0.7 mm/rev and depth of cut at level 3 – 0.75 mm.
3. The optimum cutting parameter for Surface roughness obtained at combination of A3B1C2 i.e. speed at level 3 - 1200 rpm, feed at level 1 - 0.3 mm/rev and depth of cut at level 2 – 0.50 mm.
4. The dominant factor affecting material removal rate is speed which has 38.37% contribution, followed by depth of cut having 30.37% contribution and feed having 17.66% contribution.
5. The dominant factor affecting surface roughness is feed which has 63.42% contribution, followed by speed having 26.65% contribution and depth of cut having 7.20% contribution.

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