INTERNATIONAL JOURNAL OF ADVANCE RESEARCH, IDEAS AND INNOVATIONS IN TECHNOLOGY

IJARIIT

ISSN: 2454-132X
Impact factor: 4.295
(Volume 4, Issue 3)
Available online at https://www.ijariit.com/

Optimization of machining parameters in CNC turning with varying of insert nose radius

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ABSTRACT

The objective of the study is to evaluate the effect of machining parameters on the Material Removal Rate and Surface Roughness in CNC Turning by implementing Taguchi technique. Based on the Taguchi method, turning experiments were designed and conducted on Nylon rods. CNC Turning is a machining process which is used for removing the unwanted material from the cylindrical surfaces of the work piece. In this era of manufacturing, Material Removal Rate (MRR) and surface roughness qualities are of primary concern. Taguchi method has been employed with L36 orthogonal array. Four cutting parameters namely cutting speed, feed, depth of cut and Insert Nose Radius is selected. Two different values are selected for insert nose radius and three values are selected for each of the other parameters. Turning operations are performed for maximum Material Removal Rate and minimum surface roughness response values. The material selected for machining is Nylon which is a thermoplastic material and the tools used for machining are of rigid Cast Iron with solid carbide inserts and AP68 servo oil is used as the coolant. Material Removal Rate is calculated for 36 experiments and surface roughness values are measured. Taguchi method in MINITAB software is used for optimization and the optimum values of the four parameters namely cutting speed, feed, depth of cut and insert nose radius to obtain a combination of higher material removal rate and lower surface roughness.

Keywords: *Nylon rods, CNC turning, L36 orthogonal array, MINITAB*

1. INTRODUCTION

Now a day 's machining time and the cost is the main concern in any industry. In order to decrease these parameters to increases, the material removal rate and surface roughness should decrease. Thermoplastic materials are most commonly used in various applications because which provide more strength and cheap. Computer Numerical Control (CNC) is one in which the motions of a machine tool are controlled by means of a prepared program which contains coded alphanumeric data. CNC can be specifically defined as "The numerical control system where a dedicated, stored program computer is used to perform some or all of the basic numerical control functions in accordance with control programs stored in reading & write memory of the computer" by Electronic Industries Association (EIA).

1.1 Literature Review

The research is focused mainly on experimental, design, and optimization of various machining parameters of thermoplastic material (nylon). The quality of machined surface becomes more critical in view of the very high demand for performance, safety, reliability, and life time. Hence number of machining experimentations are conducted on different type of materials and various parameters of machining are optimized using number of optimization techniques to find the optimum values of parameters like cutting speed, feed, depth of cut, rake angle, type of lubricants and other parameters which directly or indirectly affect the surface roughness and other quality characteristics of a machined component.

W. H. Yang et al. [1] employed Taguchi method to optimize various cutting characteristics and investigate how these characteristics affect the tool life and surface roughness of the selected material. Authors selected S45C steel bars as the material and conducted various turning experiments by selecting an L9 orthogonal array. It was found that cutting speed, feed rate and depth of cut significantly affect the tool life and surface roughness. Also, ANOVA was conducted to find out which factor has the highest contribution in affecting the tool life and surface roughness. Authors found that surface roughness was greatly influenced by feed rate, depth of cut and then followed by cutting speed.
M. Nalbant et al. [2] investigated the effects of parameters on turning of AISI 1030 steel bars. Insert nose radius, feed rate

and depth of cut were the parameters selected for carrying out the turning operations. Taguchi method was implemented in designing an optimal combination of parameters. The signal-to-noise ratio and analysis of variance were employed and the performance characteristics in turning operations were studied. TiN coated tools were used for machining the steel bars. The results indicated that the insert radius and feed rate have the highest control on the surface roughness. Results also demonstrated that greater insert radius, low feed rate and low depth of cut will improve the surface roughness.

S. Shaji et al. [3] investigated the use of graphite as a lubricant in surface grinding in order to reduce the heat generated during the process. Authors also investigated the effect of factors like feed, cutting speed, infeed, mode of dressing on the grinding. The force components and the surface roughness are the quality characteristics for optimizing the selected factors. Authors also made a comparison between conventional grinding which used the general liquid as coolants and the new experimental setup of using graphite as a lubricant. The results concluded that the effect of the selected parameters was almost the same in both the types of grinding but the tangential force component and surface roughness was reduced on the application of graphite as a lubricant.

Tai-Yue Wang et al. [4] investigated the significance of the Taguchi method in improving the forecasting performance. authors implemented Taguchi method in forecasting the power requirements in Taiwan Power Company, a state-owned enterprise serving the island of Taiwan. The controllable factors were considered as data period, horizon length and the number of observations required. The L9 orthogonal array was adopted and also interactions between these three parameters were also considered. Authors concluded from the results that Taguchi method was found to be effective in determining the effect of interactions between the factors. The S/N ratios of this method provide facility to give ranking to the parameters.

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1.2 Objectives of work

The objective of this study focusing on the improving various machining parameters. Therefore, the present experimental study is to observe the match inability characteristics of nylon rods. It also investigates the effects of various process parameters like cutting speed, feed, depth of cut and inserts nose radius on the quality characteristics. MRR and surface roughness is considered to be the response characteristics. The effect of the selected parameters on the Material Removal Rate and surface roughness is studied.

2. EXPERIMENTATION

The CNC turning machine was used for experimentation. It is manufactured by ACE Designers Group Company. The experiments were performed in Indo-German Institute of Advance Technology, Visakhapatnam. Model of the machine used for experimentation was LT 16 XL CNC turning machine. The output parameters like material removal rate were calculated by using turning formulae and surface roughness values are measured by using surface roughness tester.

2.1 MATERIAL SELECTION:

Nylon rods are the material which is selected to carry out the experimentation. Much of the focus is on the study of the effect of various parameters during machining of metals and composites.

Table 1: Technical properties of nylon plastic

Density (kg/m³)	1160
Tensile strength(MPa)	70
Melting point (° C)	265
Young's modulus (GN/m²)	2.4
Percentage of elongation	90
Specific gravity	1.13
Rockwell hardness	R104
Water absorption percentage	0.60

2.2 SELECTION OF RANGE OF PARAMETERS:

The factors which mainly affect the MRR and surface roughness are identified from the literature review to be

1. Insert nose radius (mm)
2. Cutting speed (RPM)
3. Feed (mm/rev),
4. The depth of cut (mm)

Three levels each are considered for the cutting speed, feed, and depth of cut. Two levels are considered for insert nose radius. The following table shows the range of parameters selected for the experimentation:

Table 2: Selection of a range of values for parameters

FEED (mm/rev)	0.1	0.2	0.3
DEPTH OF CUT (mm)	0.4	0.6	0.8
INSERT NOSE RADIUS (mm)	0.25	0.5	-

2.3 TAGUCHI METHOD:

In recent years, the Taguchi method has become a powerful tool for improving productivity during research and development also. It is used for evaluating and implementing improvements in products, processes, materials and equipment facilities and reducing the number of defects by studying the key variables controlling the process. The combination of the design of experiments with optimization of control parameters to obtain best results is achieved in the Taguchi method. Orthogonal arrays provide a set of well balanced (minimum) experiments and Taguchi's S/N ratios which are log functions of desired output serve as objective functions for optimization help in data analysis and prediction of optimum results.

3. PLAN OF EXPERIMENTS

According to the number of parameters selected and the range of values selected for each parameter, the numbers of experiments to be conducted are to be designed. This plan of experiments is done by using orthogonal arrays of Taguchi method. Generally, as three levels for three factors and one factor with two levels are considered, there can be numerous combinations of parameters because of which a number of experiments to be conducted also increase. But the specialty of the design of experiments in Taguchi method is the design of orthogonal arrays. The orthogonal arrays are Latin squares which are designed in such a way that an optimum combination of parameters can be obtained so that the optimum response characteristic value can be obtained.

Selection of array depends upon the degrees of freedom. Generally, the degree of freedom is given as follows:

D.O.F for a factor = number of levels of that factor – 1

Hence, for a three-factor three level and one factor two level matrix, the degrees of freedom will be,

DOF for insert nose radius = (2-1) = 1
DOF for cutting speed = (3-1) = 2

PARAMETERS	LEVE 1	LEVE 2	LEVE 3
CUTTING SPEED (RPM)	1196	2393	3590

DOF for feed rate = (3-1) = 2
DOF for depth of cut = (3-1) = 2
So total degrees of freedom will be 1+2+2+2 = 7
Hence for a 7 degree of freedom matrix, L36 array has been chosen using MINITAB software

3.1 EXPERIMENTAL PROCEDURE:

1. The dimensions of the work piece are to be measured.
2. Diameter of the rods is 26.6 mm and the rods are cut into pieces of length 40mm each
3. Program code is created according to the required dimensions
4. Work piece is clamped into the jaws of the chuck
5. Work piece is held with the hand and is loaded into the three jaw chuck and is set into the chuck
6. Facing process is manually carried out to create a flat surface
7. Now the facing tool is replaced by the selected cutting tool by indexing the tool turret
8. The offset setting is done by starting with the z-point
9. The tool bit is moved closer to the work piece
10. A thin piece of paper is slide between the tool bit and the work piece
11. The tool bit is moved closer to the work piece until the paper stops sliding so that the accuracy is ensured
12. The same steps are to be repeated for the x- point also
13. Now return the tool to home and press cycle start so that the machining can be started
14. According to the parameters set and the program fed into the CNC, machining is performed
15. During the machining process lubricant that is AP 68 Servo oil is flushed so that the heat generated during machining can be reduced and tool can be rescued from any sort of damage
16. After the machining gets completed, the work piece is removed from the three jaw chuck
17. Then the other work piece is fixed into the chuck and the same process is repeated
18. Similarly all the 36 machining experiments are carried out
19. Now the material removal rates of all the work pieces are calculated using the formula
20. The work pieces are tested for their surface integrity using a surface roughness tester and the surface roughness values are noted.

3.2 SURFACE ROUGHNESS MEASUREMENT:

The surface roughness values are measured for each work piece using Mitutoyo surface roughness tester. The stylus of the drive unit moves vertically on the surface which is to be measured. The surface roughness value is displayed on the LCD unit of the surface roughness tester. Five readings of surface roughness are measured for each work piece. The average of these five readings is taken as surface roughness value of the corresponding work piece so that the obtained surface roughness value is accurate.

3.3 S/N Ratios:

Larger is better**:** This type of ratio is to be used when the response factor is desired to be maximized. For example some of the response characteristics like strength, surface finish should be maximum for any component. Hence when optimal parameters which control these response factors are to be designed, larger the better is considered.

$$\text{S/N ratio} = -10 \log_{10} \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2}$$

Where y_{ou} are the observed data, n represents the number of the experiment.

4. EXPERIMENTAL REPORTS

VALUES OF MRR AND SURFACE ROUGHNESS:

After all the nylon rod pieces are machined on CNC turning, the Material removal rates of all the 36 rods are calculated and the measured values of surface roughness are tabulated as shown in the following tables:

MRR values can be calculated using the below formula:

$$M.R.R = \pi (D_{avg})\ f\ d\ N$$

Where,

$$D_{avg} = (D_i + D_f) / 2 \quad (mm)$$

D_i is the initial diameter of the nylon rods = 26.6 mm
D_f is the final diameter of the nylon rod after machining = D_i - (2 × depth of cut)

f = feed rate (mm/rev) d = depth of cut (mm)
N = Revolutions per minute (RPM)

EXPERIMENT 1:
Initial diameter of the rod (D_i) = 26.6 mm
Feed (f) = 0.3 mm³ / rev
Cutting speed (N) = 3590 RPM
Depth of cut (d) = 0.8 mm
∴final diameter of the nylon rod (D_f) = 26.6 – (2 ×0.8)
= 25 mm

So,

$$\text{MRR} = \pi \times [(26.6 + 25)/2] \times 0.3 \times 0.8 \times 3590$$
$$= 69863.4 \text{ mm}^3/\text{min}$$

Similarly, MRR values are calculated for all the experiments.

4.1 S/N RATIO CALCULATIONS:

After calculating the MRR values and surface roughness values, the S/N ratios are to be calculated separately for MRR and surface roughness. This is done in the MINITAB software but it can also be done theoretically. Material Removal Rate should be higher in order to have reduced machining time, so higher-the better S/N ratio is chosen for calculating S/N ratio values for MRR values.

4.1.1 S/N Ratio calculations for MRR:

1. Higher-the-better:

$$\text{S/N ratio} = -10 \log_{10} \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2}$$

Here,
n = number of the experiment of which S/N ratio is being measured.
y_i= response value of the corresponding experiment

Experiment 1:

$$\text{S/N ratio} = -10 \log_{10} \frac{1}{1} \sum_{i=1}^{n} \frac{1}{69863.4^2}$$

$$= -10 \log_{10} \frac{1}{1} \left(\frac{1}{4880894659.56}\right)$$

$$= 96.8815$$

Similarly, all the S/N ratios are calculated for the experiments.

4.1.2. S/N Ratio calculations for surface roughness:

Smaller the better:

$$\text{S/N ratio} = -10 \log_{10} \frac{1}{n} \sum_{i=1}^{n} {y_i}^2$$

Experiment 1:

$$\text{S/N ratio} = -10 \log_{10} \frac{1}{1} \sum_{i=1}^{n} 3.74^2$$

$$= -10 \log_{10} \frac{1}{1} (13.9876)$$

$$= -11.4574$$

Experiment 2:

$$\text{S/N ratio} = -10 \log_{10} \frac{1}{2} \sum_{i=1}^{2} (3.74^2 + 1.24^2)$$

$$= -10 \log_{10} \frac{1}{2} (7.7626)$$

$$= -1.8684$$

Similarly, S/N ratio values are calculated for all the surface roughness values.

4.2 MEAN S/N RATIO VALUE CALCULATIONS FOR MRR:

After obtaining the values of S/N ratio for both MRR and surface roughness, mean S/N ratio values are to be calculated for both MRR and surface roughness. This is done in MINITAB software. After calculation of mean S/N ratio values, following tables are obtained.

a) Mean S/N ratio values for MRR:

Table 3: mean S/N ratio values for MRR

Response Table for Signal to Noise Ratios Larger is better

Level	INSERT NOSE RADIUS	CUTTING SPEED	FEED	DEPTH OF CUT
1	85.40	80.21	80.21	82.28
2	85.40	86.23	86.23	85.74
3		89.98	89.75	88.17
Delta	0.00	9.77	9.54	5.89
Rank	4	1	2	3

4.3 THEORETICAL CALCULATION OF MEAN S/N RATIO VALUES FOR MRR:

The mean S/N ratio values can also be theoretically calculated. Mean S/N ratio for a response characteristic is the average of S/N ratio values of each level of every individual parameter

Table 4: mean S/N ratio values at each level of parameters for MRR

symbol	Cutting parameter	S/N ratio		
		Level 1	Level 2	Level 3
A	Insert nose radius (mm)	85.40	85.40	
B	Cutting speed (RPM)	80.21	86.23	89.98
C	Feed(mm/rev)	80.21	86.23	89.75
D	Depth of cut(mm)	82.28	85.74	88.17

4.4 Mean S/N ratio values for surface roughness:

Mean S/N ratio values of surface roughness values are also obtained as follows:

Table 5: Tabulated mean S/N ratio values for surface roughness

Response Table for Signal to Noise Ratios, Smaller is better

Level	INSERT NOSE RADIUS	CUTTING SPEED	FEED	DEPTH OF CUT
1	-7.455	-3.356	-1.233	-4.228
2	-1.781	-5.371	-5.199	-5.545
3		-5.127	-7.422	-4.081
	5.674	2.014	6.188	1.464
Delta				
Rank	2	3	1	4

5. RESULTS AND DISCUSSIONS

The MRR values are calculated for all the experiments. The average surface roughness values of the work material are measured for all the experiments using Mitutoyosurf test equipment. The surface roughness values are measured at five different locations on the work piece and are the average of five values is considered for all the experiments.

Table 6: Effect of parameters on MRR:

Response Table for Signal to Noise Ratios Larger is better

Level	INSERT NOSE RADIUS	CUTTING SPEED	FEED	DEPTH OF CUT
1	85.40	80.21	80.21	82.28
2	85.40	86.23	86.23	85.74
3		89.98	89.75	88.17
Delta	0.00	9.77	9.54	5.89
Rank	4	1	2	3

This response table for S/N ratio values of MRR can be used to identify the parameter which has the highest effect on the Material Removal Rate. It means a small change in the value of this parameter leads to a significant change in the MRR of the nylon rod. This is done by calculating the difference between the maximum and minimum values of S/N ratios for each level of every individual parameter. Here the difference between the maximum and minimum values at each level can be calculated as follows:

Table 7: Max-min values of S/N Ratios for each level of parameters for MRR

symbol	Cutting parameter	MAX-MIN
A	Insert nose radius	(85.40-85.40) = 0
B	Cutting speed	(89.98-80.21)= 9.77
C	Feed	(89.75-80.21)= 9.54
D	Depth of cut	(88.17-82.28)= 5.89

The parameter which is having highest difference between the maximum and minimum S/N ratio of corresponding levels is said to be the most significant factor which has the highest effect on Material Removal Rate. Hence, from the above table, it is clearly identified that out of all the values of difference of maximum and minimum values, cutting speed has the highest difference value. So, it can be concluded that cutting speed is the most significant factor. Hence it is assigned a rank 1 in the response table obtained from the MINITAB as seen in table 4.5. Similarly, the next highest difference value is of the feed rate. It means the second most significant factor which has the highest effect on MRR is feed rate and it is assigned a rank 2.

5.1 Effect of parameters on surface roughness:

Observe the response table for mean S/N ratio values of surface roughness as shown in table 8:

Response Table for Signal to Noise Ratios Smaller is better

Level	INSERT NOSE RADIUS	CUTTING SPEED	FEED	DEPTH OF CUT
1	-7.455	-3.356	-1.233	-4.228
2	-1.781	-5.371	-5.199	-5.545
3		-5.127	-7.422	-4.081
Delta	5.674	2.014	6.188	1.464
Rank	2	3	1	4

The table shows the average values of S/N ratios for each level of parameters of surface roughness which is obtained from the software. They can be calculated theoretically also. For example,

Mean S/N ratio value of level 1 of cutting speed =
(-12.8493+ -9.3669+ -9.7710+ -4.0279+0.6303+ 1.3100+ -3.5795+ 3.3498+-2.9226+-0.5061+-2.5421)/11
= - 3.356

Similarly, all the mean S/N ratio values are obtained for surface roughness. To study the effect of the parameters on surface roughness, again the difference between maximum and minimum values of parameters for all the levels are to be considered.

Table 9: Calculated values of difference of maximum and minimum s/n ratio values for surface roughness

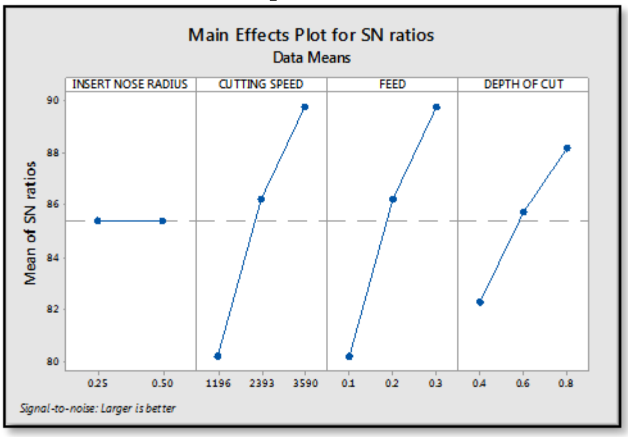
symbol	Cutting parameter	MAX-MIN
A	Insert nose radius	-1.781- (-7.455) = 5.674
B	Cutting speed	-3.356- (-5.371) = 2.014
C	feed	-1.233- (-7.422) = 6.188
D	Depth of cut	-4.081- (-5.545) = 1.464

Now to find out the most significant factor, the parameter with the highest difference should be considered. It can be identified from the above table that feed has the highest difference between maximum and minimum values. Hence it is considered to be the most significant factor which affects the surface roughness. Hence it is assigned rank 1. The next most significant factor is the insert nose radius which is followed by cutting speed and depth of cut.

5.2 Optimization of parameters for MRR

Using the S/N ratios the factors which are most significant for MRR and surface roughness are obtained. Now the effect of each individual parameters on the MRR and also surface roughness are obtained from the graphs.

Plot 1: Main effect plots for S/N ratios of MRR



The following graph obtained gives a detailed view of how each parameter that is inserted nose radius, cutting speed, feed, depth of cut have an influence on the Material Removal Rate. Generally, a parameter with a higher value of S/N Ratio is the optimum parameter which yields an optimal value of the response character

From the graph, optimal parameter range of all the parameters can be obtained. The optimal value of each parameter gives an optimum range for Material Removal Rate. The followings are the conclusions that can be obtained from the graph:

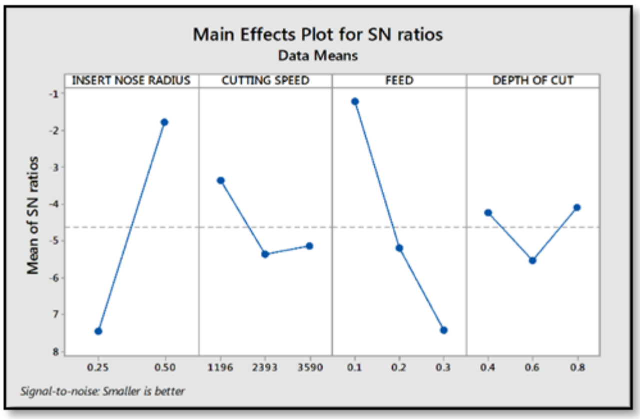
The first parameter (A) that is inserted nose radius has no effect on the Material Removal Rate. It indicates that even if there is a change in the insert nose radius value keeping the other parameter values constant, we can observe no change in the material removal rate of nylon rod during machining. A larger value of cutting speed which is at level 3 (3590 RPM) leads to a higher value of Material Removal Rate. A larger value of feed rate that is at level 3 (0.3 mm/rev) corresponds to a higher Material Removal Rate. A higher value of the depth of cut at level 3 that is 0.8 mm leads to an increased Material Removal Rate.

Thus the optimal parameters for having an increased Material Removal Rate are A-B3-C3-D3. The sequence of the most significant parameters for MRR obtained is B3-C3-D3-A

5.3 Optimization of parameters for surface roughness

The effect of each individual parameters on the surface roughness is obtained from the following graph

Plot 2: Main effect plots for s/n ratios of surface roughness



The following graph shows how insert nose radius, cutting speed, feed, depth of cut have an influence on the surface roughness. A parameter with a higher value of S/N Ratio is the optimum parameter which yields an optimal value of the response character and shows higher optimality.

The followings are the conclusions that can be obtained from the graph: A larger value of insert nose radius that is at level 2 (0.5 mm) helps in reduction of surface roughness. It means in order to have a lower surface roughness, the nose radius should be larger. A lower value of cutting speed which is at level 1 (1196 RPM) gives a lower value of surface roughness. With lower feed rate that is at level 1 (0.1 mm/rev) corresponds to a lower surface roughness. A higher value of the depth of cut at level 3 (0.8 mm) resulted in an optimal Surface roughness value.

Thus the optimal parameters for having an optimal surface roughness are A2-B1-C1-D3. The sequence of the most significant parameters for surface roughness obtained is C1-A2-B1-D3

6. CONCLUSIONS

A comprehensive analysis has been done in obtaining the significance of various factors like cutting speed, feed, depth of cut and insert nose radius. In addition to it, optimizations of parameters have been carried out by using the Taguchi method. Taguchi method is found to be suitable to find out the optimal parameters to obtain higher MRR and lower surface roughness values.

Table 10: OPTIMUM conditions for MRR

PARAMETER		VALUE
Insert Nose Radius (mm)		No effect
Cutting speed	(RPM)	3590
Feed rate	(mm/rev)	0.3
Depth of cut	(mm)	0.8

The sequence of the most significant parameters for MRR obtained is B3-C3-D3-A. It means cutting speed is the most significant factor which influences MRR which is then followed by feed, depth of cut. Insert nose radius is found to have no effect on the MRR in machining of nylon rods.

Table 11: Optimum conditions for the surface roughness

PARAMETER		VALUE
Insert Nose Radius (mm)		0.5
Cutting speed	(RPM)	1196
Feed rate	(mm/rev)	0.1
Depth of cut	(mm)	0.8

The sequence of the significant parameters for surface roughness obtained is C1-A2-B1-D3. It means the most significant parameter for surface roughness is feed rate followed by insert nose radius, cutting speed and depth of cut.

7. REFERENCES

[1] W.H. Yang, Y.S. Tang, "Design optimization of cutting parameters for turning operations based on Taguchi method", *Journal of Materials Processing Technology*, 1998, vol. 84, pp. 122-129.

[2] S. Thamizhmanii , S. Saparudin, "Analyses of surface roughness by turning process using Taguchi method", *Journal of achievement in Materials and Manufacturing Engineering*, 2007, Vol.20, Issues1-2, pp. 503-506

[3] N. Satheesh Kumara, Ajay Shetty, Ashay Shetty, Ananth K, Harsha Shetty, "Effect of spindle speed and feed rate on the surface roughness of Carbon Steels in CNC turning", *Procedia Engineering*, 2012, vol. 38, pp. 691 – 697.

[4] Ilhan Asilturk, Harun Akkus, "Determining the effect of cutting parameters on surface roughness in hard turning using the Taguchi method", *Journal of Measurement*, 2011, vol.44, pp. 1697–1704.

[5] P.G. Benardos, G.C. Vosniakos, "Predicting surface roughness in machining: a review", *International Journal of Machine Tools & Manufacture*, 2003, vol.43, pp.833-844.

[6] S. Shaji, V. Radhakrishnan, "Analysis of process parameters in surface grinding with graphite as lubricant based on the Taguchi method", *Journal of Materials Processing Technology*, 2003, vol.141, pp.51-59.

[7] Julie Z. Zhang , *Joseph C. Chenb, E. Daniel Kirby*, Surface roughness optimization in an end-milling operation using the Taguchi design method", *Journal of Materials Processing Technology*, 2007, vol.184, pp.233-239

