Research Paper

TOOL LIFE AND SURFACE ROUGHNESS OPTIMIZATION OF PVD TiAlN/TiN MULTILAYER COATED CARBIDE INSERTS IN SEMI HARD TURNING OF HARDENED EN31 ALLOY STEEL UNDER DRY CUTTING CONDITIONS

Y.B. Kumbhar, C.A. Waghmare

Address for Correspondence

Department of Mechanical Engineering, Rajarambapu Institute of Technology, Islampur, Maharashtra, India-415414

ABSTRACT

Tool wear and surface roughness prediction plays a significant role in machining industry for proper planning and control of machining parameters and optimization of cutting conditions. In this paper, Taguchi approach is used to find optimum process parameters for turning while semi hard machining of hardened EN31 alloy steel. A L9 orthogonal array, signal-to-noise ratio and analysis of variance (ANOVA) are applied to study performance characteristics of machining parameters (cutting speed, feed rate and depth of cut) with consideration of surface finish and tool life. The conclusions revealed that the feed rate was the most influential factor on the surface roughness and tool life. Experimental results are provided to illustrate the effectiveness of the proposed approach.

1. INTRODUCTION

The challenge of the mass production firms is focused mainly on the achievement of high quality, in terms of work piece dimensional accuracy, surface finish, high production rate, less wear on the cutting tools. As technological development in manufacturing industry growing, companies are switching to coated grades of carbide tools from regular carbide grades for machining operations of hardened steels[10]. The last decade has been dominated by physical vapor deposited (PVD) coated carbide tools. Nowadays, thin advanced multilayer coatings deposited by physical vapor deposition (PVD) technique on tungsten carbide substrate material are used in order to increase wear resistance and reduce insert chipping. Tool wear, cutting force, surface roughness and cutting power are relative responses. Tool wear results in changes in tool geometry that affect cutting forces, cutting power, and surface finish [3]. It is the main factor that determines the economics in metal cutting. A lower rate of tool wear means increased tool life, better surface finish, reduced tooling cost and lower cost of production.

In case of PVD TiAlN coating, the improvement in the cutting performance is due to the oxidation resistance of TiAlN properties at higher temperature [8]. High wear resistance even at high temperatures is the outstanding property of TiAlN [10], a characteristic that makes this coating appropriate to cut abrasive work piece material such as cast iron, aluminium silicon alloys and composite materials at high speeds.

2. EXPERIMENTAL DETAILS

2.1 Workpiece materials, Cutting Tools and CNC machine

The work materials used throughout this work were hardened EN31 bearing steels. The work material EN31 bearing steel contain Carbon C 0.95 - 1.10 %,Chromium Cr 1.30 - 1.60 %,Manganese Mn 0.25 % Max.,Silicon Si 0.15 - 0.30 %,Phosphor P 0.03 % Max.,Sulphur S 0.025 % Max. For heat treatment of EN31 steels, the workpieces were normalized at 850°C for 2 h and quenched with oil. Several tempering temperatures were selected to prepare specimens of various hardness values. It was tempered for 1.5 h at 210°C; resulting in a hardness of 40 HRc. Samples to be cut were in the cylindrical form of steel bars with diameter of 40 mm, length of 120 mm. These bars were machined under dry condition. The machine used for the turning tests was a Jyoti DX200 industrial type of CNC lathe machine. The lathe equipped with variable spindle speed from 50 rpm to 4500 rpm, and a 10 kW motor drive was used for the tests.

The cutting insert used for the experiment is WIDIA make TN10U grade DNMG150604 PVD coated TiAlN/TiN coated Carbide inserts. The overall coating thickness of insert is 3 to 5 µm. The substrate material of the insert consists of tungsten carbide with 11.5 % cobalt binder.

Surface finish values (Ra - arithmetic average) was measured using a Mitutoyo surface roughness tester (SJ-201) within the sampling length of 2.5 mm. Flank wear on the cutting insert was measured after every five cuts on the work piece using the trinocular microscope. For this an eyepiece with laser engraved measuring scale which can measures the length up to 1 micron is used to measure flank wear. Uniform wear criterion of 0.3 mm and a maximum wear criterion of 0.5 mm when machining steel during turning operation is used. The tool life was determined according to the recommendation of the International Organization for Standardization (ISO) criteria (the period of cutting time until the average flank wear reached 0.3 mm or the maximum flank wear land VBmax=0.6 mm).

The important controlling process parameters in turning include cutting speed (V), feed rate (f), depth of cut (D). In turn rake angle (γ), side cutting edge angle (X), end cutting edge angle (‘X) nose radius and free angle are set as constant parameters.

Table 1: Machining settings used in the experiments

Parameters/Factors	Unit	Level 1	Level 2	Level 3
A: Cutting speed	m/min	180	200	220
B: Feed rate	mm/rev	0.1	0.12	0.14
C: DOC	mm	0.5	0.7	0.9

The level of cutting parameter ranges and the initial parameter values were based on the real industry practice for machining hardened EN alloy steel by one of Indian local automotive company. The graphs, models, and tables presented in the following sections were produced using the design of experiments (DOE) and analysis modules of the software package MINITAB ® 16.1.

2.2 The Taguchi method and design of experiments

Taguchi’s method of experimental design provides a simple, efficient, and systematic approach for the optimization of experimental designs for performance quality and cost [5]. The experimental results were obtained using design of experiment (DOE) technique by Taguchi approach. Taguchi espoused an excellent philosophy for quality control in the manufacturing industries [6].His philosophy has far reaching consequences, yet it is founded on three very simple and fundamental concepts[5]. The whole of the technology and techniques arise entirely out of these three ideas. These concepts are as follows:

- Quality should be designed into the product and not inspected into it.
- Quality is best achieved by minimizing the deviation from a target.
- The cost of quality should be measured as a function of deviation from the standard and the losses should be measured system-wide.

In the Taguchi method the results of the experiments are analyzed to achieve one or more of the following three objectives [8]:

- To establish the best or the optimum condition for a product or a process
- To estimate the contribution of individual factors
- To estimate the response under the optimum conditions

The optimum condition is identified by studying the main effects of each of the factors. The process involves minor arithmetic manipulation of the numerical results and usually can be done with the help of a simple calculator. The main effects indicate the general trend of the influence of the factors [3].

Knowing the characteristic, i.e., whether a higher or lower value produces the preferred result, the levels of the factors which are expected to produce the best results can be predicted. Depending upon the type of response, the following three types of S/N ratios are employed in practice:

Higher the Better:

(S/N) HB = -10 log (MSDHB) …… (1)

Where,

$$MSDHB = \frac{1}{R}\sum_{i=1}^{R}\left(\frac{1}{Yi}\right)^2$$

MSDHB = Mean Square Deviation for higher-the- better response

Lower the Better:

(S/N) LB = -10 log (MSDLB) ……. (2)

Where

$$MSDLB = \frac{1}{R}\sum_{i=1}^{R}(Yi)^2$$

MSDHB =Mean Square Deviation for Lower-the-better response

Regardless of the category of the performance characteristics, the greater S/N ratio corresponds to the better performance characteristics. Therefore, the optimal level of the process parameters is the level with the highest S/N ratio [9].

Table 1 indicates the factors and their levels. To select an appropriate orthogonal array for the experiments, the total degrees of freedom (DOF) need to be computed. The DOF for the orthogonal array should be greater than or at least equal to those for the design parameters. In this study, an L9 orthogonal array with four columns and nine rows was used (Table 4). This array has eight DOF and it can handle three-level design parameters. The surface roughness and tool life results were subject to the analysis of variance (ANOVA).

3. ANALYSIS AND THE DISCUSSION OF EXPERIMENTAL RESULTS

Table 2 shows the experimental results for the surface roughness and tool life and corresponding S/N ratios using Eqs. 1 and 2. The mean S/N ratio for each level of the other machining parameters was calculated in a similar manner and the results are shown in Tables 3 and 4, respectively additionally, the total mean S/N ratio is computed by averaging the total S/N ratios based on the data presented in Table 2.

Table 2: Experimental results for the surface roughness and tool life and corresponding S/N ratios

Sr. No	A	B	C	AVG SR (µm)	S/N Ratio For SR	AVG TL (min.)	S/N Ratio For TL
1	1	1	1	0.7545	1.94456	42.21	32.0102
2	1	2	2	1.2287	-2.04164	27.48	28.9214
3	1	3	3	1.7145	-4.76886	21.89	26.4886
4	2	1	2	0.9847	0.29817	40.38	31.9566
5	2	2	3	1.7547	-4.65982	27.47	28.6258
6	2	3	1	2.0215	-6.49835	18.35	25.2386
7	3	1	3	0.7224	2.52796	24.08	26.8297
8	3	2	1	1.6487	-3.93429	15.21	23.9387
9	3	3	2	2.1787	-6.39306	13.59	22.8197

3.1 Effect of Cutting speed, Feed and Depth of cut on Surface Roughness

The effect of parameter cutting speed, feed and depth of cut on the surface roughness values is shown in figure 1 for mean values. Effect of cutting speed is decreasing with increase in spindle speed up to 200 m/min. beyond that it is increasing. So the optimum cutting speed is level 2 i.e. 200 m/min.Effect of feed rate is decreasing with increase in feed rate. So the optimum feed rate is level 2 i.e. 0.12 mm/rev.Effect of DOC is increasing with increase in depth of cut. So the optimum depth of cut is level 2 i.e. 0.7 mm.

Significance of machining parameters (difference between max. and min. values) indicates that Feed rate is significantly contributing towards machining performance as difference gives higher values (Table 3).Therefore, most influencing parameter is feed rate.

The signal to noise ratio analysis showed that optimized process parameters corresponding to Surface roughness are (Table:3): Vc, 180 m/min; f, 0.10mm/rev.; DOC, 0.9 mm.

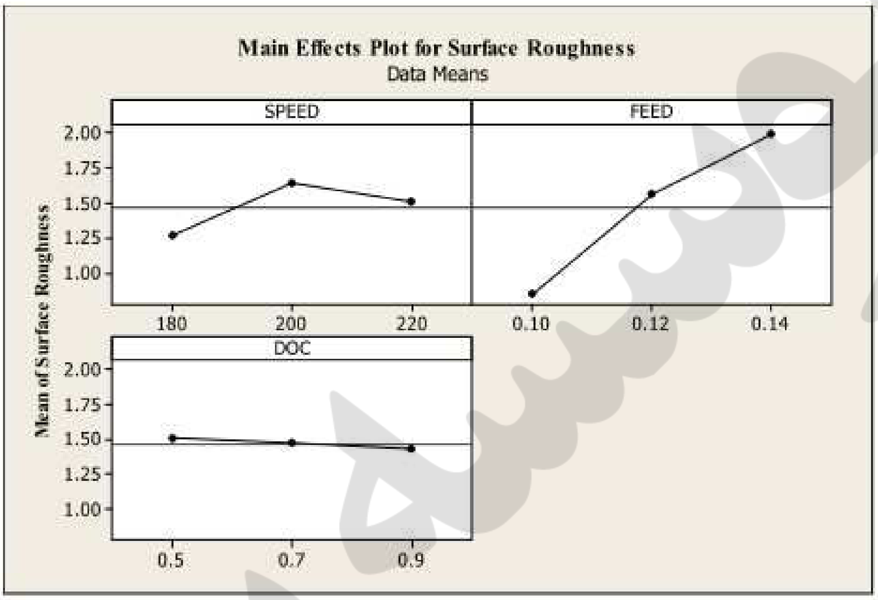

Figure 1: Main Effects plot for SR

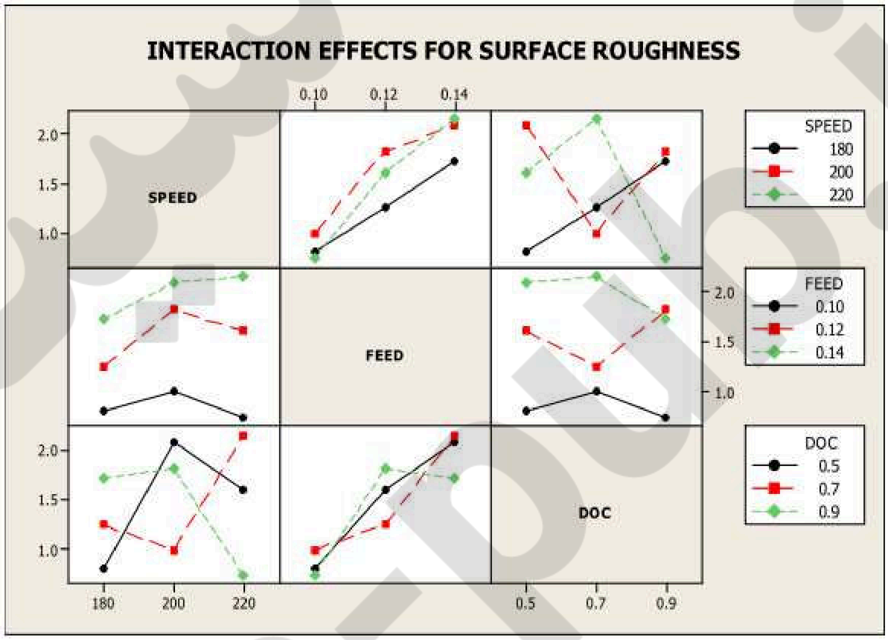

Figure 2: Full Interaction plot matrix for SR

Table 3: Response table mean S/N ratio for Surface roughness factor and significant interaction

	LEVEL	SPEED	FEED	DOC
Mean S/N ratio	1	-1.622*	1.590*	-2.829
	2	-3.620	-3.545	-2.712
	3	-2.600	-5.887	-2.300*
	Delta(Max-Min)	1.998	7.477	0.529
	Rank	2	1	3

(* indicates optimum level)

For the tool-work piece combination and cutting condition selected, a cutting speed of 180 m/min, a feed rate of 0.10 mm/min and a depth of cut of 0.9 mm will yield the lowest surface roughness and highest surface finish.

3.2 Effect of Cutting speed, Feed and Depth of cut on Tool Life

The effect of parameter cutting speed, feed and depth of cut on the surface roughness values is shown in figure 3 for mean values. Its effect is decreasing with increase in spindle speed up to 200 m/min. beyond that it is still decreasing. Hence the optimum cutting speed is level 1 i.e. 180 m/min.For the feed rate its effect is decreasing with increase in feed rate. So the optimum feed rate is level 1 i.e. 0.10 mm/rev.For the depth of cut its effect is increasing with increase in depth of cut up to level 2 then it is decreasing. So the optimum depth of cut is level 2 i.e. 0.7 mm.

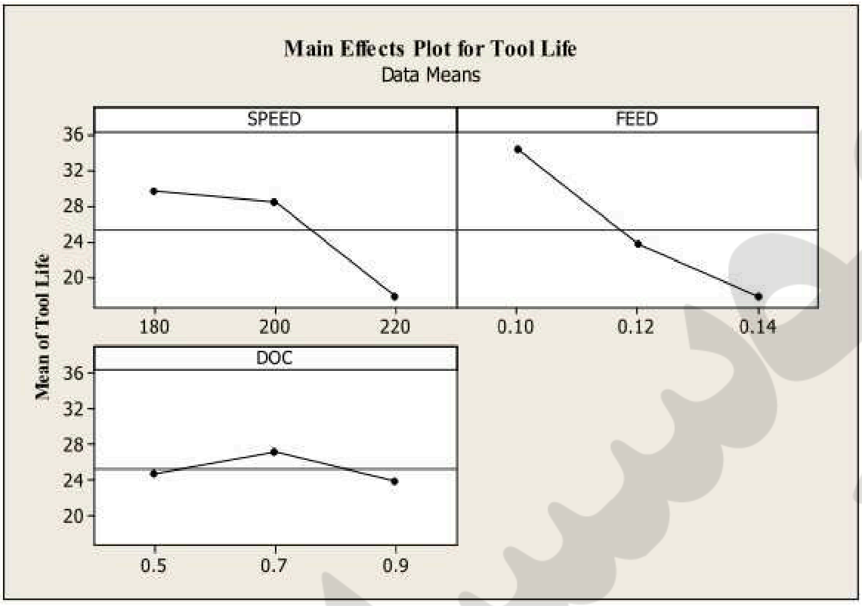

Figure 3: Main Effects plot for TL

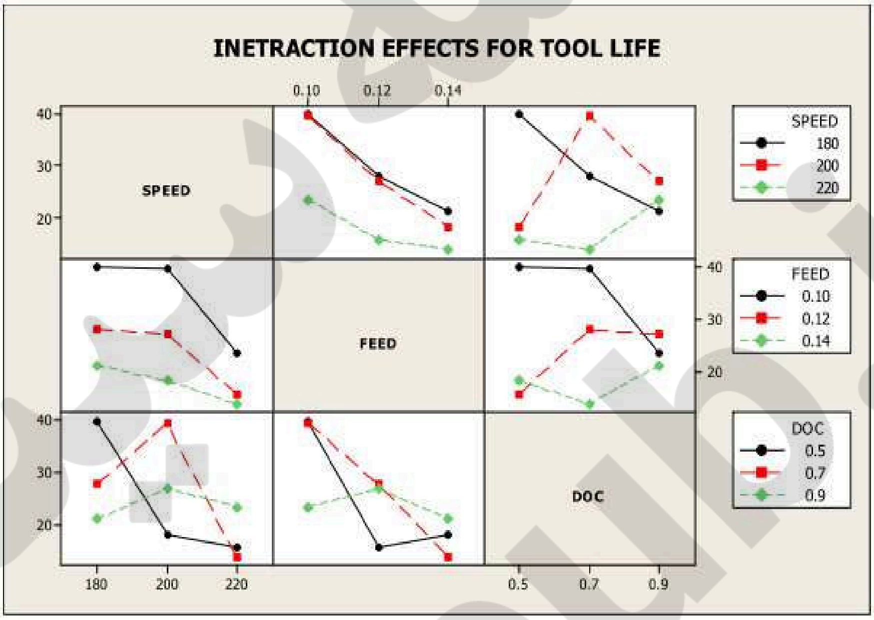

Figure 4: Full Interaction plot matrix for Tool Life

Significance of machining parameter for tool life was determined by signal to noise ratio analysis as shown in above table. In this table underlined values show corresponding highest S/N ratio values showing best levels for each process parameter to get best tool life.

Significance of machining parameters (difference between max. and min. values) indicates that Feed ate is significantly contributing towards machining performance as difference gives higher values (Table 4).Therefore, most influencing parameter is feed rate for optimizing tool life.

For the tool-work piece combination and cutting condition selected, a cutting speed of 180 m/min, a feed rate of 0.10 mm/min and a depth of cut of 0.7 mm will yield the highest Tool life.

Table 4: Response table mean S/N ratio for Tool life factor and significant interaction

	LEVEL	SPEED	FEED	DOC
Mean S/N ratio	1	29.14*	30.27*	27.06
	2	28.61	27.16	27.90*
	3	24.53	24.85	27.31
	Delta	4.61	5.42	0.84
	Rank	2	1	3

(* indicates optimum level)

Interaction plots for Tool life and surface roughness show that speed and feed interactions affect the most to the machining performance of TiAlN coated carbide cutting tool inserts in turning hardened EN31 alloy steel in dry conditions.

3.3 Analysis of variance (ANOVA)

Taguchi method cannot judge and determine effect of individual parameters on entire process while percentage contribution of individual parameters can be well determined using ANOVA. MINITAB software of ANOVA module was employed to investigate effect of process parameters (Cutting speed, feed rate, depth of cut).The significant parameters influencing the Tool Life and Ra in the turning process with TiAlN coated insert are determined using analysis of variance (ANOVA). It helps in formally testing the significance of all main factors and their interactions by comparing the mean square against an estimate of the experimental errors at specific confidence levels.

Analysis of variance is a method of portioning variability into identifiable sources of variation and the associated degree of freedom in an experiment. The frequency test (F-test) is utilized in statistics to analyse the significant effects of the parameters, which form the quality characteristics.

The results of ANOVA for the surface roughness are shown in Tables 5. This analysis is carried out for a significant level of α=0.05 (confidence level of 95%).

The main effect of feed (the most significant parameter), Cutting speed (Significance below the feed rate) are significant. It is evident that 86.67% feed is contributing on surface roughness than other cutting parameters. The cutting speed is the next contributing factor whose contribution is 9.45% and lowest contribution from depth of cut which is 0.325%.

The results of ANOVA for the Tool Life are shown in Tables 6. This analysis is carried out for a significant level of α=0.05 (confidence level of 95%). The main effect of feed (the most significant parameter), Cutting speed (Significance below the feed rate) are significant. From the values of above table it is evident that 58.82% feed is contributing on Tool life than other cutting parameters. The cutting speed is the next contributing factor whose contribution is 35.86 % and lowest contribution from depth of cut which is 2.39 %.

Results obtained from Taguchi method's Signal to noise ratio analysis closely match with ANOVA analysis as in both analyses Feed rate is most significant parameter and second significant parameter is cutting speed for best values of surface roughness and tool life. Depth of cut is least significant parameter in all results.

4. CONFIRMATION EXPERIMENTS

To verify the results obtained from taguchi method, three confirmation run experiments are performed.

The test conditions are within the range of the optimum levels obtained before. Experimental results are for surface roughness and tool life are shown blow.

Table 7 shows the results of the confirmation experiments using the optimal machining parameters for surface roughness. If we take initial parameter settings as Vc, 220 m/min; f, 0.12 mm/rev.; DOC, 0.9 mm; then surface roughness obtained experimentally is 1.78 µm, hence surface roughness is decreased by 2.80 times. So, the surface roughness is greatly improved by using the approach adopted in this thesis.

Table 5: Analysis of Variance of SN ratios for Surface roughness

Sources Of Variation	Sum of Squares (SS)	Mean Squares (MS)	F Ratio (MS/Error)	P Value	% contribution
SPEED	0.21884	0.10942	2.67	0.272	9.45
FEED	2.00516	1.00258	24.47	0.039	86.67
DOC	0.00754	0.00377	0.09	0.916	0.325
Residual Error	0.08195	0.04098			3.54
Total	2.31349				100

Table 6: Analysis of Variance of SN ratios for Tool Life

Sources Of Variation	Sum of Squares (SS)	Mean Squares (MS)	F Ratio (MS/ Error)	P Value	% contribution
SPEED	259.11	129.53	12.2	0.075	35.86
FEED	424.98	212.49	20.1	0.047	58.82
DOC	17.28	8.64	0.82	0.550	2.39
Error	21.11	10.55			2.92
Total	722.49				100

Table 8 shows the results of the confirmation experiments using the optimal machining parameters for tool life. By taking initial parameter settings as Vc, 220 m/min; f, 0.12 mm/rev.; DOC, 0.9 mm; then tool life obtained experimentally is 26.48 minutes, the tool life is increased by 1.61 times.

From the confirmation tests, good agreement between the predicted machining performance and the actual machining performance were observed. Additionally, the experimental results confirmed the validity of the applied Taguchi method for enhancing the machining performance and the optimizing the turning parameters. The surface roughness and tool life are greatly improved by using the approach

Table 7: Confirmation test for surface roughness (Ra)

Optimum values	Predicted Ra(µm)	S/N Ratio obtained	Experimental Average Ra (µm)	Error %
Vc, 180 m/min; f, 0.10 mm/rev.; DOC, 0.9 mm;	0.6065	2.9075	0.6345	3.39

Table 8: Confirmation test for Tool Life (min)

Optimum values	Predicted Tool Life Value	S/N Ratio obtained	Experimental Average TL (min)	Error %
Vc, 180 m/min; f, 0.10 mm/rev.; DOC, 0.9 mm;	44.7167	34.529	42.75	4.68

5. CONCLUSIONS

From the analysis of the results in the turning process using the conceptual signal-to-noise (S/N) ratio approach, analysis of variance (ANOVA), regression analysis and Taguchi's optimization method, the following can be concluded from the present study:

- Statistically designed experiments based on Taguchi methods were performed using L9 orthogonal arrays to analyse the tool wear and surface roughness as response variables. Conceptual S/N ratio and ANOVA approaches for data analysis drew similar conclusions.
- Maximum Tool Life is obtained at a cutting speed of 180 m/min, a moderate feed rate of 0.10 mm/revolutions and a depth of cut of 0.7 mm.
- Highest surface finish (lowest Ra) is obtained at a cutting speed of 180 m/min, a moderate feed rate of 0.10 mm/revolutions and a depth of cut of 0.9mm.
- The improvement of the surface roughness from the initial machining parameters to the optimal machining parameters is about 280%, whereas the tool life is improved by 161%.
- Interaction plots for Tool life and surface roughness show that speed and feed interactions affect the most to the machining performance of TiAlN coated carbide cutting tool inserts in turning hardened EN31 alloy steel in dry conditions.
- The results of ANOVA for Tool life show that feed rate is most significant parameter (contribution 59%) which affects the Tool life than other cutting parameters. The cutting speed is the next contributing factor whose contribution is 35.86 % and lowest contribution from depth of cut which is 2.39 %.
- The results of ANOVA for surface roughness show that feed rate is most significant parameter (contribution 87 %) which affects the Tool life than other cutting parameters. The cutting speed and DOC are least significant parameters

REFERENCES

1. Ty G. Dawson and Thomas R. Kurfess, "Tool Life, Wear Rates, And Surface Quality In Hard Turning", *2nd International Machining and Grinding Conference*, SME Paper No. MR97-224, 1997.
2. J.A. Arsecularatne , L.C. Zhang, C. Montross," Wear and tool life of tungsten carbide, PCBN and PCD cut-

ting tools", *International Journal of Machine Tools & Manufacture,* 482–491, 2006.
3. Kalpakjian, *Manufacturing Engineering and Technology*, Addison-Wesley, 2008.
4. Hari Singh & Pradeep Kumar," Tool wear optimization in turning operation by Taguchi method", *Indian Journal of Engineering & Materials Sciences,* Vol. 11, February 2004, pp. 19-24
5. J.A. Ghani ,I.A. Choudhury, H.H. Masjuki," Wear mechanism of TiN coated carbide and uncoated cermets tools at high cutting speed applications", *Journal of Materials Processing Technology,* 153–154 1067–1073 , 2004.
6. An Hu Ping, Rui Zhi Yuan Wear Mechanism of coated tool during high speed machining", *International conference on digital manufacturing and automation,* 482–491, 2010.
7. Farhad Kolahan1, Mohsen manoochehri," Application of Taguchi Method and ANOVA Analysis for Simultaneous Optimization of Machining Parameters and Tool Geometry in Turning", *World Academy of Science, Engineering and Technology,* 48–58, 2011.
8. Guosheng Su," Wear characteristics of nano TiAlN-coated carbide tools in ultra-high speed machining of AerMet100s", *Wear,* 124–131, 2012.
9. Ahmet Hasçalık & Ulaş Çaydaş," Optimization of turning parameters for surface roughness and tool life based on the Taguchi method", *International Journal Advanced Manufacturing Technology,* 38:896–903, 2008.
10. Childs, *Metal Machining-Theory and Applications*, John Wiley & Sons, 2008.