Optimization and Effect of Process Parameters on Tool Wear in Turning of Titanium Alloy under Different Machining Conditions

M. Venkata Ramana, G. Krishna Mohan Rao, and D. Hanumantha Rao

***Abstract*—To obtain safe, environmental and economical benefits of machining, the research has been carrying out to reduce the use of cutting fluid during machining. One of the alternatives to dry and flooded machining is Minimum Quantity Lubrication from the point of cost, ecology and human health issues. This paper deals with the optimization of process parameters in turning of Titanium alloy (Ti-6Al-4V) under different machining conditions using Taguchi's Robust Design Methodology on tool wear. The control factors selected are type of machining environment, cutting speed, feed rate, depth of cut and type of carbide tool material. From Analysis of Means, it is found MQL and uncoated tool shown in better performance on reduction of tool wear rate. From the Analysis of Variance (ANOVA), it is found that the cutting speed has more influence in optimizing the tool wear rate.**

***Index Terms*—Turning, titanium alloy, carbide tool, Taguchi's design methodology, tool wear, cutting fluids.**

I. Introduction

The Titanium (Ti-6Al-4V) is an Alpha-Beta grade-5 Titanium Alloy. Higher difficulties are expected when machining Titanium alloys due to its mechanical properties especially the hardness and the tensile stress at high temperatures, differences of structure with a variable quantity of the alpha phase, morphology of the transformed beta phase, very low thermal conductivity, relatively low modulus of elasticity and high chemical reactivity with tool material. Ti-6Al-4V is the most widely used in variety of weight reduction applications such as aerospace and jet engine components; automotive and marine equipment; medical applications such as implants, turbine blades, etc. The advantages of Ti-6Al-4V alloys are less weight, high tensile strength, bio-compatibility, low thermal and electrical conductivity, corrosion resistance, etc. Cutting fluids are introduced in the machining zone to improve the tribological characteristics of machining processes to dissipate the heat generated, improving tool life, reducing work piece thermal deformation, improving surface roughness and flushing away chips from the cutting zone. The main problem associated with the machining of Titanium is tool wear. It was found that the straight tungsten carbide (WC/Co) cutting tools continue to maintain their superiority machining titanium alloys [1]. The advantages of flooded/conventional use of cutting fluids in machining, however questioned lately due to their negative effects such as employee health and environmental pollution and cost. To improve the machinability of Titanium alloys, the special methods are introduced such as rotary cutting, the use of ledge tools, Minimum Quantity Lubrication (MQL) etc [1].

The cutting performance on Ti-6Al-4V alloy with synthetic oil is found to be better when compared to dry and servo cut oil with water in reducing surface roughness. The results from ANOVA shows that, while machining Ti-6Al-4V alloy, the synthetic oil is more effective under high cutting speed, high depth of cut and low feed rate compared to dry and servo cut oil with water conditions[2]. In the recent years a lot of research has been carried out to avoid the use of cutting fluids in machining. Because of them some alternatives have been sought to minimize or even avoid the use of cutting fluid in machining operations in which, one of the alternative is MQL.

The role of MQL on cutting temperature, tool wear, chip formation and product quality in turning AISI-1040 steel by uncoated carbide insert was carried out and the results are compared among dry, flooded and MQL machining. The experimental results indicate that MQL enables substantial reduction in the cutting temperature, tool wear, dimensional inaccuracy depending upon the levels of the cutting speed and feed rate [3]. Furthermore, MQL provides environment friendliness, maintaining neat, clean and dry working area, avoiding inconvenience and health hazards due to heat, smoke, fumes, gases, etc. and preventing pollution of the surroundings and improves the machinability characteristics. The optimum amount of MQL was found during machining of brass using K10 carbide tool was carried out. The Analysis of Means (ANOM) and Analysis of Variance (ANOVA) on multi-response signal-to-noise (S/N) ratio were employed for determining the optimal parameter levels and identifying the level of importance of the process parameters on surface roughness and specific cutting force [4].

The special techniques of MQL, High Pressure Coolant, Cryogenic Cooling, Compressed Air Cooling and use of Solid Lubricants/Coolants developed for turning of difficult to cut material. These techniques have resulted in reduction in friction and heat at the cutting zone, hence improved productivity of the process [5]. The MQL technique is used in turning to determine the tool wear reduction. The result

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shows that the lubricating on rake surface by the MQL technique does not produce evident of wear reduction. Tool life time of a tip used in dry cutting conditions is similar to that of a tip lubricated by MQL on the rake. Lubricating the flank surface of a tip by the MQL technique reduces the tool wear and increases the tool life. Traces of lubricant compounds have been found on the worn surfaces only when MQL has been applied on the flank surface [6].

A thorough study of literature suggests that the machining of Titanium alloy is very difficult compared to other alloy materials. Very few works have been done on the optimization of process parameters in turning process of Ti-6Al-4V alloy with different processes parameters. However very few works have carried out on machining of Titanium alloys under different lubricant conditions such as dry, flooded and Minimum Quantity Lubricant (MQL).

II. Methodology

In this work, Taguchi robust design methodology[7] is applied to obtain the optimum conditions for lower tool wear rate in turning of titanium Ti-6Al-4V alloy under dry, flooded and MQL conditions. Statistical software Minitab is used to obtain results for Analysis of Mean (ANOM) and Analysis of Variance (ANOVA).

III. Experimental Details

The aim of this work is to find out the set of optimum values for the control factors in order to minimize tool wear rate using Taguchi's robust design methodology. The Minitab software is used to generate the linear model for ANOVA. The experiments are carried out on a GEDEEWEILER LZ350 lathe. The work piece material used is Ti-6Al-4V alloy of 120mm long and 50mm diameter in the form of bar.

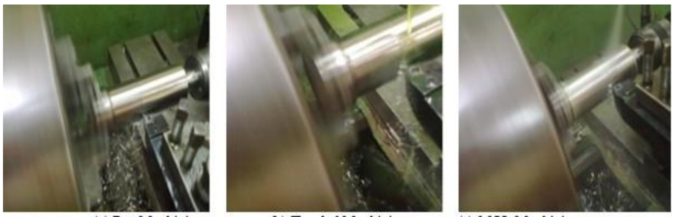
The different types of carbide tools used in this work are made by SECO with same tool specifications. The tool holder used for machining is PSBNR16-4R174.3-2525-12 specification and it is made by sandvik coromant. Three different types of carbide tools used are uncoated grade 883, CVD coated TM 4000 and PVD coated TS 2000.

A. Selection of Control Factors, Levels and Orthogonal Array

A total of five process parameters with three levels have been chosen as the control factors such that the levels sufficiently covers wide range. The five control factors selected are type of machining environment(A), cutting speed (B), feed rate (C), depth of cut (D) and type of carbide tool material (E). The control factors and their levels are shown in Table 1. Selection of particular Orthogonal Array (O.A) from the standard O.A. depends on the number of factors, levels of each factor, interactions and the total degrees of freedom. Based on these factors, the required minimum number of experiments to be conducted are 27, the nearest O.A. fulfilling this condition is L27 (35) and the factors assigned to this O.A. is shown in Table II.

B. Cutting Fluid/ Lubricant

The experiments are conducted under different machining environments. Fig. 1(a) shows photographic view of dry machining in which cutting fluid is not used. Fig. 1(b) shows photographic view of flooded machining. The cutting fluid used in flooded machining is GANDHAR made synthetic water soluble coolant. It contains 1: 20 volumetric concentration and flushed to the cutting zone at rate of 3 liters / min. Fig. 1(c) shows photographic view of MQL machining. MQL setup consists of air compressor, spray gun with fine nozzle and cutting fluid chamber. The cutting fluid used is same as flooded machining. Cutting fluid is supplied to spray gun at the rate of 100 ml/hr, which is mixed with compressed air (3bar) in the mixing chamber of spray gun. Then the mixture of air and cutting fluid (mist) is supplied and impinged with high pressure and velocity at the cutting zone by spray gun nozzle. The mist reaches as close to the chip–tool and the work–tool interfaces as possible. The MQL spray is concentrated on rake and flank surface along the cutting edges to protect the tool faces, minimize the friction, increase the cooling, lubrication abilities and reduce the tool wear.



(a) Dry Machining (b) Flooded Machining (c) MQL Machining

Fig. 1. Photographic view of turning under different machining conditions.

TABLE I: Control Factors and Levels

Factors/ Levels	Type of machining environment (A)	Speed (B) (m/min)	Feed rate (C) (mm/rev)	Depth of Cut(D) (mm)	Type of Tool Material (E)
1	Dry	63 (B1)	0.206 (C1)	0.6 (D1)	Uncoated (E1)
2	Flooded	79 (B2)	0.274 (C2)	1.0 (D2)	CVD Coated (E2)
3	MQL	99 (B3)	0.343 (C3)	1.6 (D3)	PVD Coated (E3)

C. Experimental Procedure

Titanium specimens are prepared for conduct of the experiments. The specimens have turned on lathe according to L27 Orthogonal Array (O.A) as shown in Table II under dry, flooded and MQL conditions. The tool makers microscope is used to measure flank wear on cutting tool for each experiment as shown in Fig. 2. The summary of average tool wear rate and its S/N ratio of flank wear are shown in Table II. Optimization of process parameters is carried out using Taguchi Robust design methodology and statistical Minitab software [7], [8]. Tool wear is measured by observing and measuring the wear as it develops. The flank wear is generally measured from the original cutting edge. If the flank wear is not uniform along the flank face, the mean value tool wear (VB) is determined.

IV. Experimental Results and Discussions

In this work, the performance characteristics namely tool wear has to be reduced and hence "smaller the better type" quality characteristic has been selected. The S/N ratio associated with this characteristic is shown in equation (1)

Smaller the better:

$$S/N = -10 \log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (1)$$

where y is the observed data.

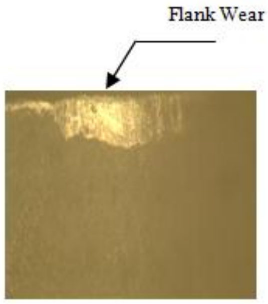


Fig. 2. Flank wear on uncoated carbide cutting tool.

A. Optimization of Cutting Parameters

To arrive optimum process parameters, Taguchi's robust design methodology has been successfully employed in order to minimize the tool wear. After analysis of data from the robust design of experiments, the optimum process parameters found. The mean effect plot for tool wear is shown in Fig. 3. The condition for the optimum level is the maximum S/N ratio. It is observed that, the MQL is found to be optimum compared to dry and flooded conditions and uncoated tool is found to be optimum compared to CVD and PVD coated tools. The average value of the performance characteristic for each parameter is referred as mean response at different levels. Thus, the optimal process parameters obtained are MQL machining environment (A3), cutting speed at 63m/min (B1), feed rate at 0.274 mm/rev.(C2), depth of cut at 1.0 mm (D2) and uncoated tool (E1) levels.

TABLE II: L27 ORTHOGONAL ARRAY WITH TOOL WEAR AND S/N RATIO

S.No	A	B	C	D	E	VB	S/N ratio
1	Dry	B1	F1	D1	T1	0.080	21.87
2	Dry	B1	F2	D2	T2	0.075	22.47
3	Dry	B1	F3	D3	T3	0.095	20.33
4	Dry	B2	F1	D2	T3	0.090	20.86
5	Dry	B2	F2	D3	T1	0.095	20.43
6	Dry	B2	F3	D1	T2	0.110	19.17
7	Dry	B3	F1	D3	T2	0.210	13.55
8	Dry	B3	F2	D1	T3	0.115	18.77
9	Dry	B3	F3	D2	T1	0.115	18.77
10	Flooded	B1	F1	D1	T1	0.055	25.15
11	Flooded	B1	F2	D2	T2	0.065	23.71
12	Flooded	B1	F3	D3	T3	0.080	21.87
13	Flooded	B2	F1	D2	T3	0.080	21.93
14	Flooded	B2	F2	D3	T1	0.070	23.01
15	Flooded	B2	F3	D1	T2	0.085	21.39
16	Flooded	B3	F1	D3	T2	0.190	14.41
17	Flooded	B3	F2	D1	T3	0.070	23.01
18	Flooded	B3	F3	D2	T1	0.085	21.39
19	MQL	B1	F1	D1	T1	0.060	24.43
20	MQL	B1	F2	D2	T2	0.060	24.31
21	MQL	B1	F3	D3	T3	0.075	22.47
22	MQL	B2	F1	D2	T3	0.065	23.71
23	MQL	B2	F2	D3	T1	0.060	24.31
24	MQL	B2	F3	D1	T2	0.105	19.56
25	MQL	B3	F1	D3	T2	0.180	14.88
26	MQL	B3	F2	D1	T3	0.075	22.47
27	MQL	B3	F3	D2	T1	0.095	20.43

B. Interaction Effect of Process Parameters on Tool Wear

The interaction effects between two factors on S/N ratio are examined to determine the relative importance of the parameters on tool wear portion under different coolant conditions. Fig. 4 shows the interaction plots between cutting speed and type of coolant condition. Under dry condition, the effect of cutting speed on tool wear from 63 to 79 m/min and 79 to 99 m/min is maximum. Similarly under flooded and MQL conditions the effect of cutting speed on tool wear from 63 to 79 m/min and 79 to 99 m/min is maximum. As seen from Fig. 4, as the machining environment changes, S/N ratios increases from dry to flooded and flooded to MQL. This indicates that the tool wear decreases from dry to flooded and flooded to MQL. Hence, reduction of tool wear is observed in MQL compared to dry and flooded machining.

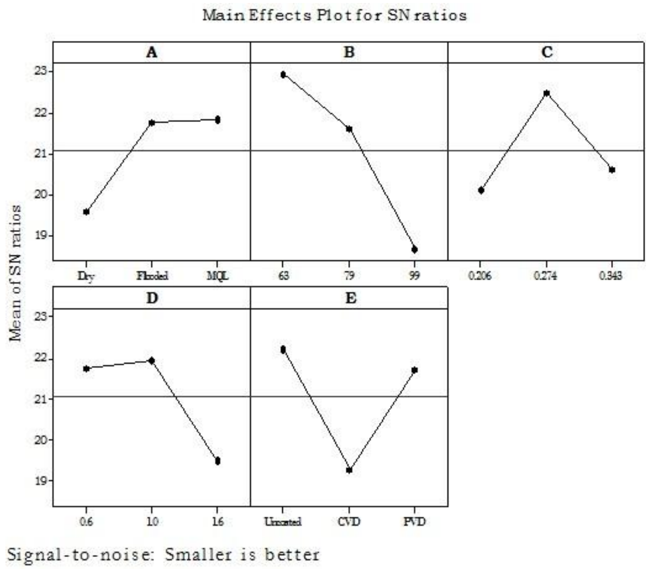


Fig. 3. Main effect plots for tool wear.

Fig. 5 shows the interaction plots between feed rate and type of coolant condition. Under dry condition, the effect of feed rate on tool wear from 0.206 to 0.274mm/rev is maximum and 0.274 to 0.343 m/min is minimum. Similarly under flooded condition the effect of feed rate on tool wear from 0.206 to 0.274mm/rev is maximum and 0.274 to 0.343 m/min is minimum and under MQL condition the effect of feed rate on tool wear from 0.206 to 0.274mm/rev and 0.274 to 0.343 m/min are maximum. As seen from Fig. 5, as the machining environment changes, S/N ratios increases from dry to flooded and flooded to MQL. This indicates that the tool wear decreases from dry to flooded and flooded to MQL expect feed rate at 0.343 mm/rev. Hence, it is observed the tool wear is less in MQL compared to dry and flooded machining.

Fig. 6 shows the interaction plots between depth of cut and type of coolant condition. Under dry condition, the effect of depth of cut on tool wear from 0.6 to 1.0 mm is minimum and 1.0 to 1.6 m/min is maximum. Similarly under flooded condition the effect of depth of cut on tool wear from 0.6 to 1.0 mm is minimum and 1.0 to 1.6 mm is maximum and under MQL condition the depth of cut on tool wear from 0.6 to 1.0 mm/rev is minimum and 1.0 to 1.6 m/min is maximum. As seen from Fig. 6, as the machining environment changes, S/N ratios increases from dry to flooded and flooded to MQL. This indicates that the tool wear decreases from dry to flooded and flooded to MQL expect depth of cut at 0.6 mm. Therefore, compare to dry and flooded, with MQL machining tool wear is less.

Fig. 7 shows the interaction plots between type of tool material and coolant condition. Under dry condition, the effect and change of tool material on tool wear from uncoated to CVD and CVD to PVD is maximum. Similarly under flooded condition the effect and change of tool material on tool wear from uncoated to CVD and PVD to CVD is maximum and under MQL condition effect and change of tool material on tool wear from uncoated to CVD and PVD to CVD is maximum. From Fig. 7, it also indicates that, change of tool material on tool wear from uncoated to PVD is minimum. As seen from Fig. 7, as the machining environment changes, S/N ratios increases from dry to flooded and flooded to MQL in the case PVD tool. This indicates that the tool wear decreases from dry to flooded and flooded to MQL. Whereas, as the machining environment changes, S/N ratios increases from dry to flooded and decreases from flooded to MQL. This indicates that the tool wear decreases from dry to flooded and increases from flooded to MQL.

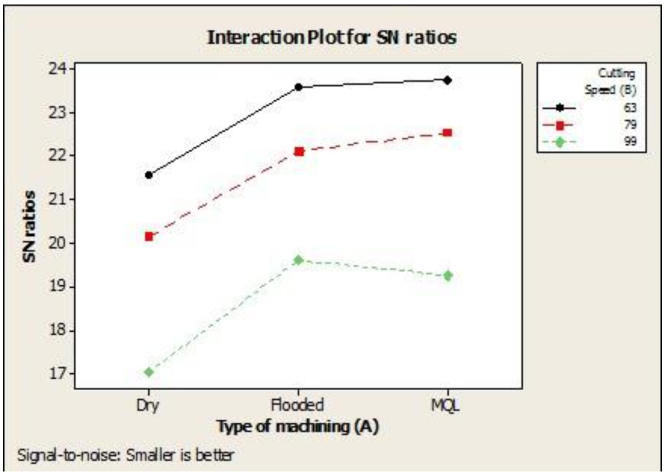


Fig. 4. Interaction effect plot of cutting speed and type of coolant.

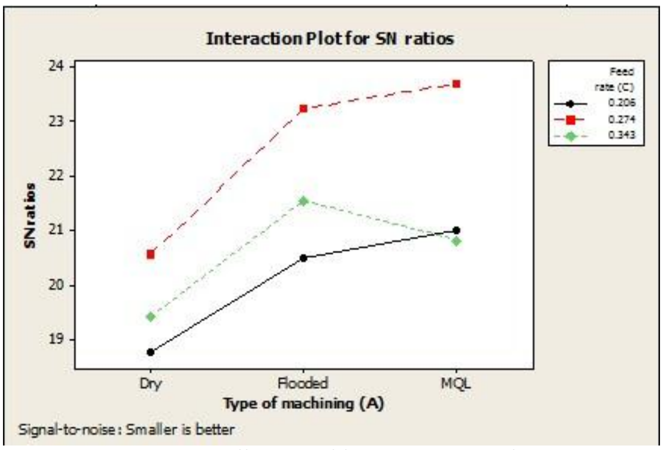


Fig. 5. Interaction effect plot of feed rate and type of coolant.

C. Influence of Process Parameters

Analysis of Variance is carried out to evaluate influence and performance of each process parameter in machining. The results of ANOVA on performance characteristic are shown Table III. The P-value in Table III indicates the significant condition of each factor. As seen from ANOVA Table III to minimize the tool wear, cutting speed has highly responsive (35.165 %) in optimizing the performance characteristics followed by tool material, depth of cut, feed rate and coolant condition.

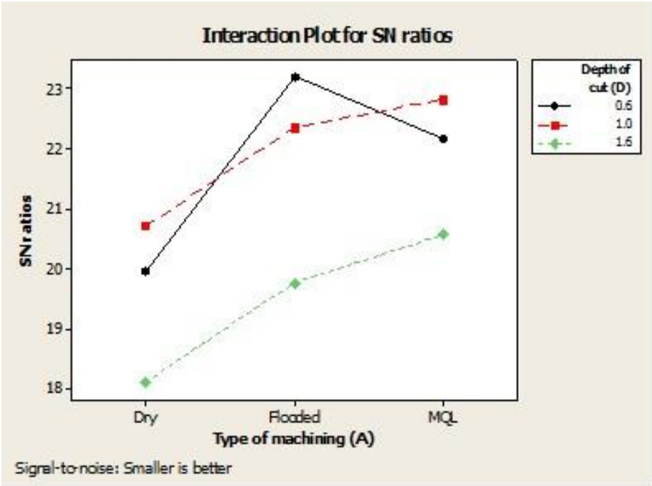


Fig. 6. Interaction effect plot of depth of cut and type of coolant.

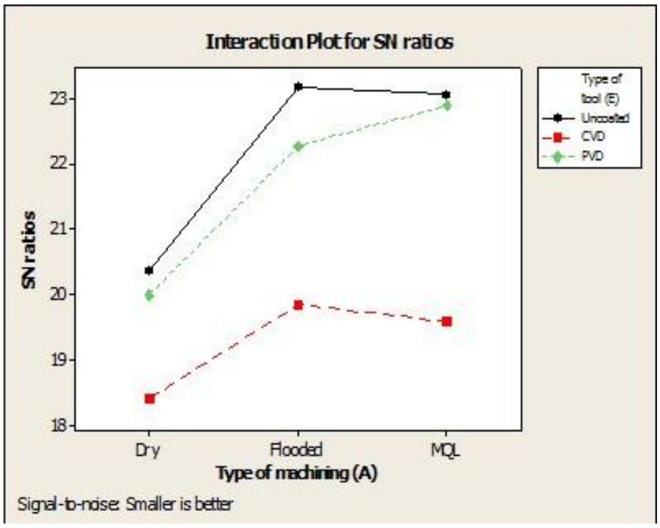


Fig. 7. Interaction effect plot of type of tool material and type of coolant.

The error contribution 3.49% is observed from ANOVA. Further the interaction between type of coolant condition with cutting speed, feed rate, depth of cut and tool material are insignificant and shown in Table III with bold letters. The predictive or additive model is developed using optimum conditions of the S/N ratio as shown in Eq. (2).

$$\eta_{predicted} = Y + (A3\text{-}Y) + (B1\text{-}Y) + (C2\text{-}Y) + (D2\text{-}Y) + (E1\text{-}Y) \qquad (2)$$

where Y is average S/N ratio; $A3$, $B1$, $C2$, $D2$ and $E1$ are optimum cutting parameter. The predicted S/N ratio is 27.79 dB. The verification test results must be confirmed to the predicted results. Hence with the optimum conditions, the verification experiment is conducted and corresponding S/N ratio is (ηexpt) 27.68 dB In Table III, D. O. F means Degrees of Freedom, S.S means Sum of Squares, P means Predicted value (If the predicted value of a factor is <0.05 then the factor is said to be significant). This analysis is carried out at a significant level of 5% and confidence level of 95%.

TABLE III: SUMMARY OF ANOVA ON TOOL WEAR

Factors(Source)	S.S	D.O.F	M.S.S	F-RATIO	SS[1]	P-Value	ρ %
Type of machining environment (A)	0.00638	2	0.00319	29.71	0.00638	0	7.6899
Cutting speed (B) (mpm)	0.02918	2	0.01459	135.84	0.02918	0	35.165
Feed rate (C) (mm/rev)	0.01174	2	0.00587	54.64	0.01174	0	14.144
Depth of cut(D) (mm)	0.01454	2	0.00727	67.67	0.01454	0	17.518
Type of Tool (E)	0.01825	2	0.00912	84.95	0.01825	0	21.99
A*B	**0.00041**	4	0.0001	0.95	0.00041	**0.451**	
A*C	**0.00055**	4	0.00014	1.28	0.00055	**0.301**	
A*D	**0.00069**	4	0.00017	1.59	0.00069	**0.204**	
A*E	**0.00027**	4	6.9E-05	0.64	0.00027	**0.64**	
Error	0.0029	27	0.00011		0.0029		3.4946
Total	0.0849	53					
Total After excluding insignificant (Bold letters) factors	0.08299						100

D. Regression Analysis

The Mathematical predictive model is to developed with help of multiple regression analysis using the predictors' viz. Type of machining environment, cutting speed, feed rate, depth of cut and type of carbide tool materials. The statistical tool Minitab is used to develop predictive models for tool wear.

After Regression analysis, the final second order regression model is given by:

$$VB = 0.591 - 0.00444 \times X1 + 0.0178 \times X2 - 0.00340 \times Vc - 3.07 \times F - 0.09318 \times D + 0.0378 \times Y1 - 0.00444 \times Y2 + 5.34 \times F \times F + 0.0565 \times D \times D + 0.000031 \times Vc \times Vc \qquad (3)$$

where VB = Tool wear rate; Vc = cutting speed; F=feed rate; D= depth of cut; and $X1$, $X2$ and $Y1$,$Y2$ are the indicator variables of type of machining environment and tool materials respectively.

V. CONCLUSIONS

Based on the results of these experimental investigations, the following conclusions are drawn:

- The machining performance of MQL machining shows favorable and better results compared to dry and flooded conditions.
- The MQL machining shows advantage mostly by reducing tool wear as well as environmental problems, which reduces the friction between the chip - tool interaction.
- The optimal process parameters for minimizing tool wear are MQL machining environment, cutting speed at 63 m/min, feed rate at 0.274mm/rev, depth of cut at 1.0mm and uncoated tool.
- Using ANOVA, the effect each individual factors on tool wear found to be significance and the contribution of cutting speed is more followed by tool material, depth of cut, feed rate and coolant condition in order to minimizing tool wear.
- The confirmation experiments are revealed that Taguchi's robust design methodology is successfully verified with the optimum process parameters. The predicted model is adequate at 95% confidence level with confirmation experiment chosen for optimum quality characteristics.
- The mathematical model is developed using Multiple Regression Analysis and this model is verified successfully with experimental results.

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