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Research Article

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Experimental and Mathematical Modeling for Prediction of Tool Wear on the Machining of Aluminium 6061 Alloy by High Speed Steel Tools

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Abstract: In recent machining operation, tool life is one of the most demanding tasks in production process, especially in the automotive industry. The aim of this paper is to study tool wear on HSS in end milling of aluminium 6061 alloy. The experiments were carried out to investigate tool wear with the machined parameters and to developed mathematical model using response surface methodology. The various machining parameters selected for the experiment are spindle speed (N), feed rate (f), axial depth of cut (a) and radial depth of cut (r). The experiment was designed using central composite design (CCD) in which 31 samples were run on SIEG 3/10/0010 CNC end milling machine. After each experiment the cutting tool was measured using scanning electron microscope (SEM). The obtained optimum machining parameter combination are spindle speed of 2500 rpm, feed rate of 200 mm/min, axial depth of cut of 20 mm, and radial depth of cut 1.0mm was found out to achieved the minimum tool wear as 0.213 mm. The mathematical model developed predicted the tool wear with 99.7% which is within the acceptable accuracy range for tool wear prediction.

Keywords: End Milling; Tool Wear; Minimum quantity lubrication (MQL); Aluminum; Response Surface Methodology

1 Introduction

Dimensional inaccuracy of a machined surface may be classified into two, namely; surface location error and surface roughness. Surface location error is due to tool compliance that causes it to deflect under action of cutting forces leading to the cutting edges of the tool being deviated from the intended location and profile [1, 2]. Surface roughness is the inherent irregularities left by a single-point tool like turning or milling tool, on a machined surface, surface roughness is mainly considered as the most important feature of engineering surfaces due to its crucial influence on the mechanical and physical properties of a machined part [3]. The irregularity of a machined surface is an indication of relative vibration between the work piece and cutting tool during machining operation [4].

The parameters for machining process are expected to affect the relative vibrations on all components of the surface roughness, machining parameters such as the spindle speed, the axial depth of cut, the radial depth of cut and the feed rate, these are the most easily controlled parameters of the machining operation at the disposal of the operator either choose or vary continuously in process. Tool wear being a tribological phenomenon develops with sequence of machining and then causes progressive increase in surface roughness [5]. Tool wear has been attributed to cutting conditions, tool geometry and mechanical stiffness. Various studies have considered the behavior of tool wear under different tool-work-piece material combinations and experiments, such as the effect of flood coolant, and dry machining [6–8].

Minimum quantity lubrication (MQL) refers to the use of cutting fluids of only a little amount usually of a flow rate of 50-500 ml/hour, which is about three to four orders of magnitude lower than the amount regularly used

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in flood cooling for example, up to 10 liters of fluid can be dispersed per minute [11]. Machining with minimum quantity lubricant, is gaining acceptance as a cost saving and environmentally friendly preference in place of wet machining processes. The objective of MQL mixing system is to deliver a precise amount of aerosol. That is, the diameter of the aerosol particulates is held to a precise tolerance to maintain optimum wetting and lubrication properties [12]. Okonkwo *et al.* [13] carried out the Comparative analysis of aluminium surface roughness in end-milling under dry and MQL conditions. Were 10% boric acid was mixed with base oil SAE 40, which proved to be a feasible alternative to dry machining condition. The result obtained indicated that there is a significant improvement in machining performance with MQL when compared to dry machining. They showed that MQL can reduce the surface roughness by 20% depending upon the level of process parameters and the work piece material. Many researchers have recommended the MQL technique in machining process; [14–16] Davim *et al.* and dhar *et al.*, used this technique in a turning process and found that MQL is better than flood cooling.

Tool wear, which results in tool substitution, is the most important economic penalties to take into account during machining. Wear is commonly defined as the undesirable deterioration of a component by the removal of material from the surface of the work piece. It occurs by displacement and detachment of particles from the work piece. The mechanical properties of steel are sharply reduced due to wear [17]. Thus it is important to improve tool life, minimize the wear and optimize all the cutting parameters and factors, such as radial depth of cut, spindle speed, axial depth of cut and feed rate and cutting fluids application. In milling operations, fluids play an important role in protecting work piece and tool from corrosion and promote the chip evacuation. During machining, at all environments, work material adheres to the edges of the tool, but the quantity of adhered material varies with the type of coolant used. Diniz *et al.* [18] Found out that during the turning of hardened 52100 steel with cubic boron nitride tools at moderate cutting speeds (110 m/min), dry machining yielded lower flank wear, while directing a compressed air jet at the cutting zone caused higher flank wear. The anticipated explanation for this observation was that lack of cooling action under dry condition enhances thermal softening of work piece material, thus making cutting easier, whereas the cooling action of an air jet causes the reverse effect by promoting strain hardening in the work material. MQL was found to perform slightly better than plain compressed air, and this was explained to occur because the lubricating effect of the oil partly mitigated due to the compressed air jet of the MQL supply. Sreejith [19] Conducted investigations in the turning process of aluminium alloys and stated that when the machined speed increased from 50 to 400 m/min, the adhesion between the tool and the chip also increased correspondingly. This could be due to the increase in thermal softening of the chip as the temperature increased with the increase in cutting speed. The adhesion of the work material to the tool was observed to be very high during dry machining. The material adhesion was seen all over the tool surfaces like flank, rake and clearance surfaces especially when the speed of machining was increased from 250 to 400 m/min. The measure of the adhered material reduced considerably with flooded coolant compared to the dry machining process. During MQL machining, the amount of material adhered was seen to be more compared with flooded coolant and less compared to dry machining [20]. As the quantity of the lubricant was increased from 50 ml/h to 100 ml/h during MQL, there was no considerable reduction in the adhered material. The larger amount of adhered material during MQL conditions may be due to the tool geometry.

Aluminum is broadly used in the manufacturer industry, mechanical applications, communication industry, structural applications, cryogenic applications and extensively in the transportation industry. Aluminium has a density one third the density of steel. Even though they have lower tensile properties when compared to steel their strength to weight ratio is exceptional. It is simple to manufacture aluminium because of their good thermal and electrical conductivity and they do not exhibit a transition from ductile to brittle phase at low temperatures. They can be recycled as they are nontoxic and require less energy. Nevertheless, they do not show a true endurance limit so even at low stresses fatigue failure can occur. On the other hand aluminium alloys are favourable as structural materials because of their high specific strength and stiffness [21–25]. Due to this they are being used in automobile industries as basic constituents of internal combustion engines like cylinder blocks, cylinder heads and pistons [6].

Moreover, the accomplishments of some researchers related to the current investigation are recognized. Progress in evaluation, experimental analysis of (both dry and MQL end-milling) and the effects of cutting parameters on tool wear predictions, as they pertain to end milling process of aluminium were reviewed. Experimentally tool wear is low at the start and at the end of the cut where chip thickness is minimum and is high in the center of the work-piece where the chip thickness is maximum; this is where the problems lies on because most mathematical model could not predict the tool life accurately by developing their model with either axial depth of cut or radial depth of cut. This makes their model one sided. Hence there is need to investigate the tool wear of high speed steel (HSS) tools in the machining of the various lengths and width of the axial and radial depth of cut of the work piece. This is the focus of this study to develop a mathematical model for tool wear using the spindle speed, feed rate, radial depth of cut and axial depth of cut by multiple linear regression, analyzing the process parameters and also investigated the effective combinations between the cutting parameters.

2 Material and methods

In the experimental study, the material used was 6061 aluminium alloy. Dimensions of the specimens were 2000mm × 50mm × 10mm, which was cut into different sizes of 10, 15, 20, 25, and 30 mm, total of 31 pieces for the experiment. The cutting tools used were high speed steel (HSS) having diameter of 12 mm and number of flute 4. Before machining the high speed steel (HSS) cutter was fixed on the spindle taper of the machine, the work piece was clamped on a device mounted on top of the table of the machine and creating CNC part programs on CNC professional software for tool paths, with specific commands using different levels of spindle speed, feed rate, axial depth of cut and radial depth of cut, taking reference for Y axis, and Z axis then the end milling operation performed. After machining, the cutting tool was then examined under a scanning electron microscope to check the tool wear.

Table 1 shows the physical, mechanical, thermal and electrical properties of Al-6061 alloy and Table 2 and Table 3 also shows the chemical composition of the 6061 aluminium alloy and the important factors influencing the tool wear and there levels.

The experiment was performed on SIEG 3/10/0010 CNC vertical milling machine, the centre has three (3) planes axes namely x, y and z planes.

Response surface methodology (RSM) was employed in the experimental design using second-order rotatable central composite design. The required number of experimental runs for four-factor five levels in the C.C.D with one replication of factorial and axial parts having factorial design is thirty-one (31). Therefore the thirty-one experiments are carried out according to the unblocked central composite design (CCD). The Minitab 16 was used in analysis and presentation of results.

Table 1: Physical, mechanical, thermal and electrical properties of AL-6061 alloy.

Properties	Value	Unit
Density (ρ)	2.70	g/cm^3
Young's modulus €	68.9	GPa
Tensile strength (σt)	124–290	MPa
Elongation (ϵ) at break	12–25%	-
Poison's ratio (v)	0.33	-
Melting temperature ™	585	°C
Thermal conductivity (k)	151–202	W/(m·K)
Linear thermal expansion coefficient (α)	2.32×10^{-5}	K^{-1}
Specific heat capacity (c)	897	J/(kg·K)
Volume resistivity (ρ)	32.5-39.2	nOhm·m

3 Mathematical models

The relationship between tool wear (VBmax) and the machining parameters such as spindle speed (N), feed rate (f), Radial depth of cut (r) Axial depth of cut (a), are presented in equation (1): [16]

$$VB_{\max} = f\{N, f, a, r\} \tag{1}$$

The second-order regression equation used to represent the response tool wear (VBmax) is given by:

$$VB_{\max} = b_0 + \Sigma b_i X_i + \Sigma b_{ii} X_i^2 + \Sigma b_{ij} X_i X_j \tag{2}$$

For four factors, the chosen polynomial is given as:

$$\begin{aligned} VB_{\max} = {} & b_0 + b_1 N + b_2 f + b_3 a + b_4 r + b_{12} Nf \\ & + b_{13} Na + b_{14} Nr + b_{23} fa + b_{24} fr + b_{34} ar + b_{11} N^2 \\ & + b_{22} f^2 + b_{33} a^2 + b_{44} r^2 \end{aligned} \tag{3}$$

Where b_0 is the responses average, and b_1, b_2, b_3, and b_{44} are coefficients of regression that depend on the individual linear, interaction, and squared terms of factors. The value of the coefficient was calculated using Minitab 16 Software. The significance of each coefficient was determined by student's t-test and p-value, which are shown in Table 4 and 5. The values of p-less than 0.05 indicate that the model terms are significant. In this case, X_1, X_2, X_4 and X_1X_4 are significant model terms and X_3 has less influence on the tool wear.

The values greater than 0.10 indicate that the model terms are not significant, the final empirical relationship was constructed using only these coefficients, and the developed final empirical relationship is shown in equa-

Table 2: Chemical composition of AL-6061 alloy [5].

Element	Mg	Fe	Si	Cu	Mn	V	Ti	AL
Weigh %	0.15-1.2	0.17	0.7	0.33	0.52	0.01	0.02	Balance

Table 3: Experimental factors and their levels.

Factor	Levels				
	−2	−1	0	1	2
Spindle speed [rpm]	1500	2000	2500	3000	3500
Feed rate [mm/min]	100	150	200	250	300
Axial depth of cut[mm]	10	15	20	25	30
Radial depth of cut [mm]	1	1.5	2	2.5	3

tion (4) below:

$$\begin{aligned} VB_{\max} = {} & 0.3214 - 0.0238X_1 \\ & + 0.01909X_2 + 0.0114X_3 + 0.1187X_4 + 0.0077X_1^2 \\ & + 0.0203X_2^2 + 0.0054X_3^2 + 0.0074X_4^2 \\ & - 0.007257X_1X_2 - 0.021296X_1X_3 \\ & - 0.070204X_1X_4 - 0.007318X_2X_3 \\ & + 0.002818X_2X_4 - 0.003318X_3X_4 \end{aligned} \tag{4}$$

3.1 Analysis and Validation of Results

In order to judge the accuracy of the developed mathematical models, percentage deviation Φ_i and average percentage deviation were used. The percentage deviation Φ_i is stated thus: [13]

$$\Phi_i = \left(\frac{E_{a(p)} - E_{a(m)}}{E_{a(m)}}\right) \times 100\% \tag{5}$$

Where:Φ_i: percentage deviation of single sample data,
Ea(m): Actual value measured experimentally,
Ea(p): predicted generated by a multiple regression equation.

Similarly, the average percentage deviation is stated thus:

$$\overline{\Phi}_i = \frac{\sum_{i=1}^{n} \Phi_i}{n} \tag{6}$$

4 Result and discussion

From Table 4, shows the experimental result and the design matrix that was use in this research work, which include the coded value and the four variables such as the spindle speed, feed rate, axial depth of cut and radial depth of cut respectively.

Statistical Analysis of Variance

A response tool wear model was designed and analyzed using Minitab 16 software, Table 5 shows the Analysis of Variance (ANOVA) used to determine the effect of machining parameters on the tool wear and Tables 5 show the statistical significance of the regression model, interaction, residual error and lack-of-Fit on the tool wear.

In this investigation, the desired level of confidence was considered to be 95%. The correlation may be considered to be adequate, which provides that the calculated F value of the model developed should not go beyond the standard tabulated F value. The standard tabulated F value for 95% confidence boundary is 4.06. From Table 6, the calculated F value of the model is 2.04 for lack-of-fit is smaller than the standard value of 95% confidence limit. Thus, it is established that the mathematical model is adequate.

The regression equation that is the mathematical model for the tool wear are shown in equation (7)

$$\begin{aligned} VB_{(\max)} = {} & 0.0831 - 0.000021N \\ & + 0.000192f + 0.000932a + 0.121r \end{aligned} \tag{7}$$

This equation (7) are used to predict the response for a given levels of each factor as shown in Table 6 and Figure 1.

Similarly, the actual values gotten from the experiment and the predicted values obtained from the developed mathematical model are depicted in Figure 1. It can be seen that they have good agreement quantitatively.

Table 4: Design matrix and experimental results.

Exp No	Coded value X_1	X_2	X_3	X_4	Spindle Speed (rpm)	Feed Rate (mm/min)	Axial depth of cut (mm)	Radial depth of cut (mm)	Tool Flank Wear VB_{max}
1	−1	−1	−1	−1	2000	150	15	1.5	0.226
2	1	−1	−1	−1	3000	150	15	1.5	0.286
3	−1	1	−1	−1	2000	250	15	1.5	0.26
4	1	1	−1	−1	3000	250	15	1.5	0.293
5	−1	−1	1	−1	2000	150	25	1.5	0.237
6	1	−1	1	−1	2000	150	25	1.5	0.296
7	−1	1	1	−1	3000	250	25	1.5	0.272
8	1	1	1	−1	2000	250	25	1.5	0.299
9	−1	−1	−1	1	3000	150	15	2.5	0.34
10	1	−1	−1	1	2000	150	15	2.5	0.409
11	−1	1	−1	1	3000	250	15	2.5	0.379
12	1	1	−1	1	2000	250	15	2.5	0.424
13	−1	−1	1	1	3000	150	25	2.5	0.36
14	1	−1	1	1	2000	150	25	2.5	0.415
15	−1	1	1	1	3000	250	25	2.5	0.386
16	1	1	1	1	2000	250	25	2.5	0.421
17	−2	0	0	0	3000	200	20	2	0.264
18	2	0	0	0	1500	200	20	2	0.363
19	0	−2	0	0	3500	100	20	2	0.316
20	0	2	0	0	2500	300	20	2	0.359
21	0	0	−2	0	2500	200	10	2	0.311
22	0	0	2	0	2500	200	30	2	0.343
23	0	0	0	−2	2500	200	20	1	0.213
24	0	0	0	2	2500	200	20	3	0.445
25	0	0	0	0	2500	200	20	2	0.324
26	0	0	0	0	2500	200	20	2	0.33
27	0	0	0	0	2500	200	20	2	0.321
28	0	0	0	0	2500	200	20	2	0.328
29	0	0	0	0	2500	200	20	2	0.325
30	0	0	0	0	2500	200	20	2	0.329
31	0	0	0	0	2500	200	20	2	0.331

Table 5: Tool wear, VB_{max} estimated regression coefficients.

Term	Coef	SE Coef	T	P
Constant	0.3214	0.007259	44.284	0.000
Spindle Speed (rpm)	−0.023811	0.008973	−2.654	0.017
Feed rate (mm/min)	0.019096	0.009086	2.102	0.052
Axial Depth of Cut (mm)	0.011439	0.00845	1.354	0.195
Radial Depth of Cut (mm)	0.118727	0.00845	14.05	0.000
Spindle Speed (rpm)*Spindle Speed (rpm)	0.007765	0.018883	0.411	0.686
Feed rate (mm/min)* Feed rate (mm/min)	0.020358	0.018203	1.118	0.280
Axial Depth of Cut(mm)* Axial Depth of Cut(mm)	0.005463	0.015241	0.358	0.725
Radial Depth of Cut (mm)*Radial Depth of Cut (mm)	0.007463	0.015241	0.490	0.631
Spindle Speed (rpm)* Feed rate (mm/min)	−0.007257	0.017461	−0.416	0.683

S = 0.0202903, PRESS = 0.0240734, R-Sq = 93.69%, R-Sq (pred.) = 76.92%, R − Sq (adj.) = 88.16%

Table 6: Results of ANOVA.

Source	DF	SS	MS	F	P
Regression	14	0.097738	0.022797	45.11	0.000
Linear	4	0.091186	0.021506	52.24	0.000
Square	4	0.001294	0.000943	0.57	0.687
Interaction	6	0.005257	0.005257	2.13	0.107
Residual Error	16	0.013138	0.000505		
Lack-of-Fit	9	0.004768	0.000530	2.04	0.180
Pure Error	7	0.001819	0.000260		
Total	30	0.104325			

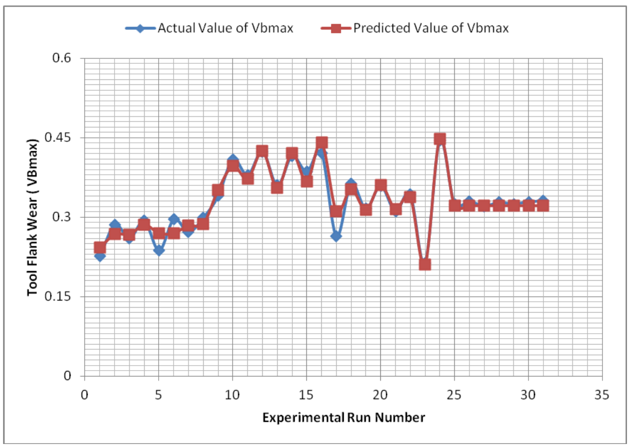

Figure 1: Comparison between Actual Value and Predicted Value of the Tool Wear.

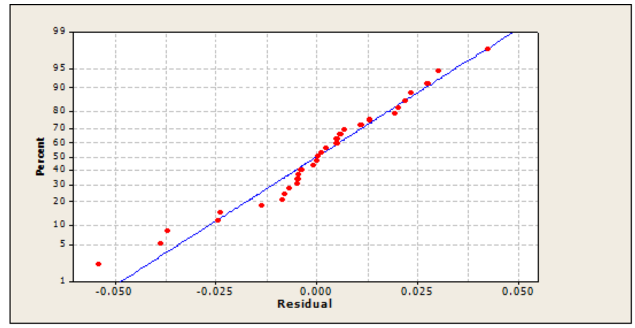

Figure 2: Normal Percent plot of residuals for tool wear.

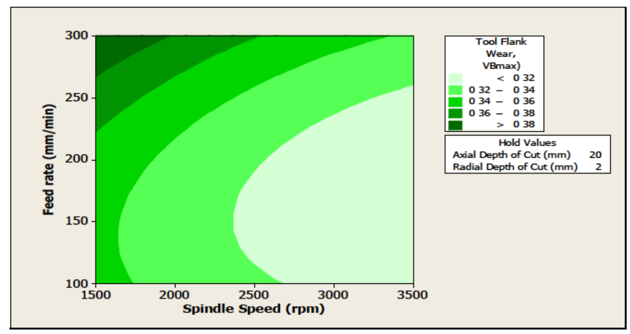

Figure 3: Contour plot of tool wear vs. feed rate and spindle speed.

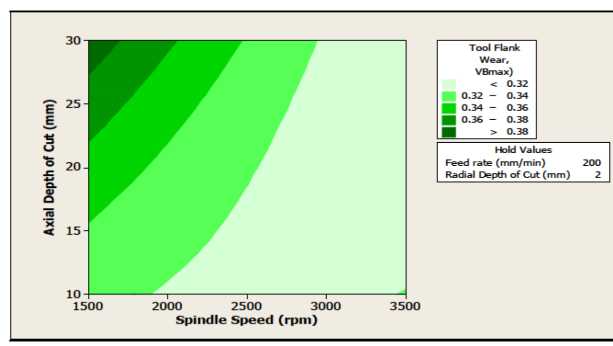

Figure 4: Contour plot of tool wear vs. axial depth of cut and spindle speed.

The accuracy of the model developed for the tool wear is tested using equation (5) and (6)

$$\overline{\Phi}_i = \left[100 - \left[\frac{8.56}{31}\right]\right] \% = 99.7\%$$

Where $\overline{\Phi}_i$: average percentage deviation of all sample data n: the size of sample data.

The result of average percentage deviation ($\overline{\Phi}_i$) showed that the mathematical model can predict the tool wear with about 99.7% accuracy, Table 7 shows the predicted value for tool wear and percentage deviation from the actual values.

The normal probability plot of residuals for tool wear is presented in Figure 2. It was observed that the residuals fall on a straight line, which means that the errors are normally distributed and the regression model is well fitted with the experimental values.

Figure 3-9 shows the four machining parameters effects on the tool wear, it shows that at low spindle speed the tool wear increases, but increase in spindle speed, decreases tool wear is observed, which could be due to the elimination of the unstable larger BUE and the chip fracture. The increase in feed rate increases the thrust force, torque and it leads to increase in tool wears and increase power consumption [21]. Increasing radial depth of cut lead to increase in chatter vibration frequency which damages the cutting tools during the milling operation and also thereby increases the tool wear, this result is in line with the observation made by Nwoke *et al.* [22] and Okokpujie *et al.* [26]. Increasing the Axial Depth of cut will slightly increase the tool wear. The general development of increase in tool wear with increase in feed rate, axial and radial depth of cut is attributed to the increase in temperature at the cutting zone.

Table 7: Comparison between actual value and predicted value of tool wear (VB_{max}).

Exp No	Spindle Speed (rpm)	Feed Rate (mm/min)	Axial depth of cut (mm)	Radial depth of cut (mm)	Tool Flank Wear VB_{max}	Predicted Tool Flank wear VB_{max}	Percentage deviation VB_{max}
1	2000	150	15	1.5	0.226	0.24236649	7.24181
2	3000	150	15	1.5	0.286	0.26793397	−6.3168
3	2000	250	15	1.5	0.26	0.26734096	2.823446
4	3000	250	15	1.5	0.293	0.28565142	−2.50805
5	2000	150	25	1.5	0.237	0.26977171	13.82773
6	2000	150	25	1.5	0.296	0.26977171	−8.86091
7	3000	250	25	1.5	0.272	0.28444249	4.574446
8	2000	250	25	1.5	0.299	0.2874284	−3.8701
9	3000	150	15	2.5	0.340	0.35180956	3.473399
10	2000	150	15	2.5	0.409	0.39644571	−3.06951
11	3000	250	15	2.5	0.379	0.37234479	−1.75599
12	2000	250	15	2.5	0.424	0.42423796	0.056123
13	3000	150	25	2.5	0.360	0.35460063	−1.49982
14	2000	150	25	2.5	0.415	0.42053316	1.333291
15	3000	250	25	2.5	0.386	0.36781808	−4.71034
16	2000	250	25	2.5	0.421	0.44100763	4.752405
17	3000	200	20	2	0.264	0.31150933	17.99596
18	1500	200	20	2	0.363	0.35304989	−2.74108
19	3500	100	20	2	0.316	0.31394662	−0.64981
20	2500	300	20	2	0.359	0.36092722	0.53683
21	2500	200	10	2	0.311	0.31549766	1.446192
22	2500	200	30	2	0.343	0.33837618	−1.34805
23	2500	200	20	1	0.213	0.21020951	−1.31009
24	2500	200	20	3	0.445	0.44766432	0.598725
25	2500	200	20	2	0.324	0.32147352	−0.77978
26	2500	200	20	2	0.330	0.32147352	−2.58378
27	2500	200	20	2	0.321	0.32147352	0.147513
28	2500	200	20	2	0.328	0.32147352	−1.98978
29	2500	200	20	2	0.325	0.32147352	−1.08507
30	2500	200	20	2	0.329	0.32147352	−2.28768
31	2500	200	20	2	0.331	0.32147352	−2.87809

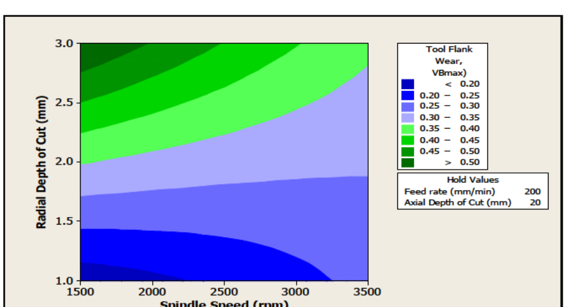

Figure 5: Contour plot of tool wear vs. Radial depth of cut and spindle speed.

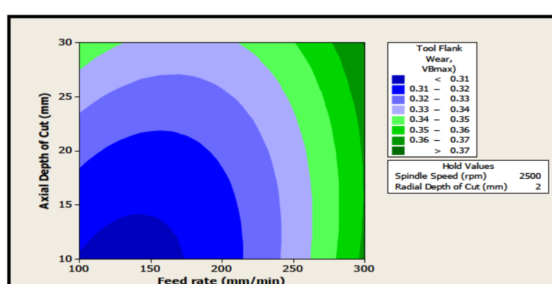

Figure 6: Contour plot of tool wear vs. axial depth of cut and feed rate.

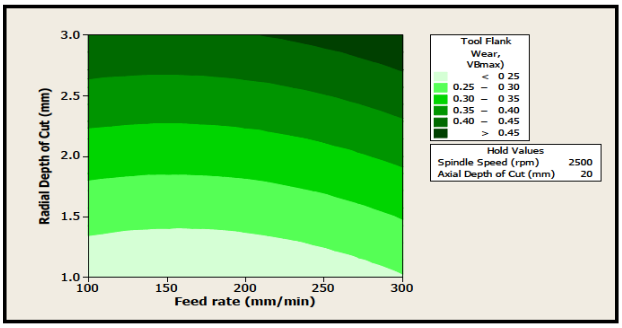

Figure 7: Contour plot of tool wear vs. radial depth of cut and feed rate.

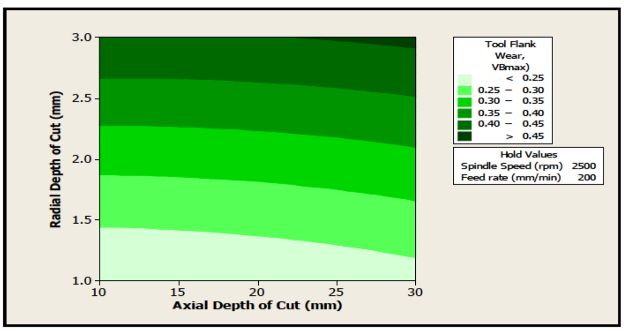

Figure 8: Surface plot of tool wear vs. radial depth of cut and axial depth of cut.

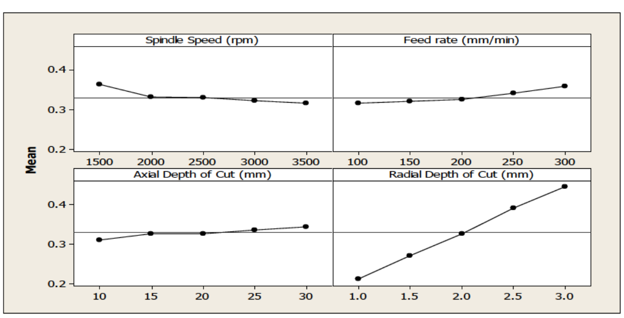

Figure 9: Effects of the Four Parameters on the Tool Wear.

5 Conclusion

The aim of this research was to develop a model to predict tool wear in CNC end milling. In this study response surface methodology (RSM) was employed to develop a mathematical model. The result of average percentage deviation shows that the mathematical model could predict the tool wear with 99.7%, which is within acceptable accuracy range, the following findings were observed.

- From the experimental analysis and the model developed, the machining parameter combination, that is spindle speed of 2500 rpm, feed rate of 200 mm/min, axial depth of cut of 20 mm, and radial depth of cut 1.0mm was found out to achieve the minimum tool wear as 0.213 mm.
- In the order of influence, radial depth of cut has great significant influence on tool wear, followed by spindle speed. However feed rate and axial depth of cut has little significant effect on tool wear

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