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Modeling and optimization of tool wear and surface roughness in turning of austenitic stainless steel using response surface methodology

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Abstract:

The wear of cutting tools remains a major obstacle. The effects of wear are not only antagonistic at the lifespan and productivity, but also harmful with the surface quality. The present work deals with some machinability studies on flank wear, surface roughness, and lifespan in finish turning of AISI304 stainless steel using multilayerTi(C,N)/Al₂O₃/TiN coated carbide inserts. The machining experiments are conducted based on the response surface methodology (RSM). Combined effects of three cutting parameters, namely cutting speed, feed rate and cutting time on the two performance outputs (i.e. VB and Ra), and combined effects of two cutting parameters, namely cutting speed and feed rate on lifespan (T), are explored employing the analysis of variance (ANOVA). The relationship between the variables and the technological parameters is determined using a quadratic regression model and optimal cutting conditions for each performance level are established. The results show that the flank wear is influenced principally by the cutting time and in the second level by the cutting speed. In addition, it is indicated that the cutting time is the dominant factor affecting workpiece surface roughness followed by feed rate, while lifespan is influenced by cutting speed.

Keywords: Flank wear, Surface roughness, Lifespan, RSM, ANOVA.

1 Introduction

The tool wear, especially the flank wear, is one of the most important aspects that affect lifespan and product quality in machining. It is a major form of tool wear in metal cutting, which adversely affects the dimensional accuracy and product quality, is the main hurdle in the wide implementation of coated carbide tools to machining of stainless steel in the industry. Practically the lifespan is evaluated by the measure of the flank wear. If it increases quickly, the lifespan becomes very short and vice versa. In finish turning, tool life is measured by the machining time taken by the same insert until the flank wear reaches its allowable limit of 0.3 mm. Wear is an important

technological parameter of control in the machining process. It is the background for the evaluation of the tool life and surface quality [1, 2]. Therefore, development of a reliable flank wear progression model will be extremely valuable.

Significant efforts have been devoted by several researchers in understanding and modeling the tool wear progression, wear mechanisms, tool lifespan and surface quality in metal cutting. In recent years, a significant emphasis has been placed in the development of predictive models in metal cutting. Analytical models are easy to implement and can give much more insight about the physical behavior in metal cutting. Kramer [3] developed a model for prediction of the wear rates of coated tools in high-speed machining of steel. The abrasive wear and the chemical dissolution were considered as dominant wear mechanisms. Singh and Rao [4] developed flank wear prediction model of ceramic inserts in hard turning. Flank wear rate was modeled considering abrasion, adhesion, and diffusion as dominant wear mechanisms. Normal load/force incurred on the flank face was modeled using experimental results. However, increase in the normal load with the progress in flank wear was not considered in the model. It is widely reported that cutting forces influence more with the progress in flank wear, which appeared as one of the most promising techniques for monitoring tool wear. Singh and Vajpayee [5] developed a flank wear model considering abrasion as the dominant wear mechanism. Yallese et al. [6] have shown that for the 100Cr6 steel, the machined surface roughness is a function of the local damage form and the wear profile of a CBN tool. When augmenting cutting speed tool wear increases and leads directly to the degradation of the surface quality. In spite of the evolution of flank wear up to the allowable limit $VB = 0.3$ mm, arithmetic roughness Ra did not exceed $0.55 \mu\text{m}$. A relation between VB and Ra in the form $Ra = k \cdot e^{\beta}(VB)$ is proposed. Coefficients k and β vary within the ranges of $0.204\text{--}0.258$ and $1.67\text{--}2.90$, respectively. It permits the follow-up of the tool wear.

A common problem in product or process design is the selection of design variable setting which meets a required specification of quality characteristics. For this purpose, among global approximation approaches, the response surface methodology (RSM) has recently attracted the most attention since it has performed well in comparison to other approaches [7, 8]. RSM consists of the following three steps: (1) data gathering, (2) modeling, and (3) optimization. Neseli et al. [9] applied response surface methodology (RSM) to optimize the effect of tool geometry parameters on surface roughness in hard turning of AISI 1040 with P25 tool. Yallese et al. found that a cutting speed of 120 m/min is an optimal value for machining X200Cr12 using CBN7020 [6]. In an original work carried out by Çaydaş [10], the effects of the cutting speed, feed rate, depth of cut, workpiece hardness, and cutting tool type on surface roughness, tool flank wear, and maximum tool–chip interface temperature during an orthogonal hard turning of hardened/tempered AISI 4340 steels were investigated. Dureja et al [11] applied the response surface methodology (RSM) to investigate the effect of cutting parameters on flank wear and surface roughness in hard turning of AISI H11 steel with a coated-mixed ceramic tool. The study indicated that the flank wear is influenced principally by feed rate, depth of cut and workpiece hardness. When turning hardened 100Cr6, Banga and Abrão [12] found that cutting speed is the most factor influencing tool lifespan. These authors have shown that PCBN cutting tools provide longer tool lifespan than both mixed and composite ceramics. A model built to evaluate the machinability of Hadfield steel using RMS and ANOVA techniques was presented by Horng et al [13]. The study revealed that the flank wear is influenced by the cutting speed while the interaction effect of the feed rate with the nose radius and the corner radius of the tool have statistical significance on obtained surface roughness.

The current study investigates the influence of cutting parameters (cutting speed, feed rate and cutting time, with a constant cutting depth $a_p = 0.15$ mm) in relation to flank wear (VB), lifespan (T) and surface roughness (Ra) on machinability. The processing conditions are turning of stainless steel (AISI 304) with CVD coated carbide tools using both response surface methodology (RSM) and

ANOVA. This latter is a computational technique that enables the estimation of the relative contributions of each of the control factors to the overall measured response. In this work, only the significant parameters will be used to develop mathematical models using response surface methodology. The latter is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which response of interest is influenced by several variables and the objective is to optimize the response.

2 Experimental procedures

2.1. Material and means

Straight turning operations were carried out on 100 mm diameter and 400 mm length bars made of AISI 304 stainless steel with the chemical specification given in table 1. Machining operations were achieved on a 6.6 KW power TOS TRENCIN model SN40 lathe. Cutting inserts used are SANDVIK “Ti(C,N)/Al₂O₃/TiN” CVD coated carbide referenced as GC2015 (SNMG 12-04-08-MF). The cutting inserts were clamped on a right-hand tool holder with designation PSBNR25x25M12. The geometry of the right-hand tool holder is characterized by the following angles: $\chi_r=+75^\circ$, $\lambda = -6^\circ$, $\gamma = -6^\circ$ and $\alpha =+6^\circ$. A roughness meter (2d) SurfTest 201 Mitutoyo was employed to measure surface roughness Ra. The length examined is 4 mm with a cut-off of 0.8 mm and the measured values of Ra are within the range 0.55 – 3.2 μm . Roughness values were obtained without disassembling the workpiece in order to reduce uncertainties due to resumption operations. Flank wear VB is usually observed in the flank face of a cutting insert. Among the different forms of tool wear, flank wear is the important measure of the lifespan as it affects the surface quality of the workpiece. Long-term wear tests have been carried out through straight turning to evaluate CVD coated carbide tool flank wear for various cutting conditions. Flank wear is measured using a binocular microscope (Visual Gage 250) equipped with (Visual Gage 2.2.0) software figure 1.

Table 1
Chemical composition of AISI 304

Composition	(Wt. %)
C	0.02
Cr	16.91
Ni	7.69
Si	0.33
Mn	1.44
Mo	0.41
Fe	72.10
Other components	1.1

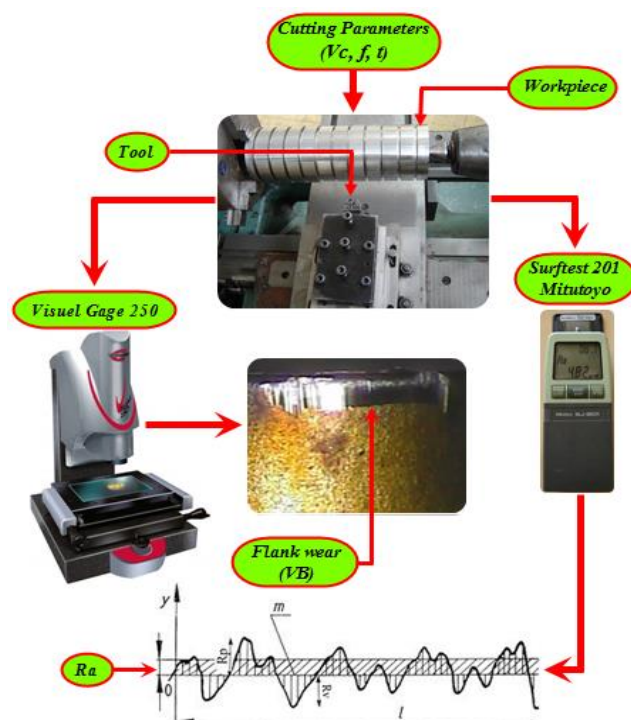


Figure 1 Illustration of measured surface roughness and flank wear

2.2. Experimental design

In order to develop the mathematical model based on RSM, two full factorials design (3^3 and 3^2) are adopted as the experimental design method. In the current study, cutting speed, feed rate and cutting time are identified as the factors which affect the responses such as surface roughness, flank wear and lifespan. Three levels are defined for each factor to investigate surface roughness and flank wear behavior (table 2). On the other hand, to investigate the lifespan behavior three levels are defined for two factors (cutting speed and feed rate) (table 3).

Table 2

Attribution levels of cutting parameters for Ra and VB

Control parameters	Unit	Symbol	Levels		
			Level 1	Level 2	Level 3
Cutting speed	m/min	Vc	280	330	400
Feed rate	mm/rev	f	0.08	0.11	0.14
Cutting time	min	t	4	10	16

Table 3

Attribution levels of cutting parameters for T

Control parameters	Unit	Symbol	Levels		
			Level 1	Level 2	Level 3
Cutting speed	m/min	Vc	280	330	400
Feed rate	mm/rev	f	0.08	0.11	0.14

2.3. Response surface methodology (RSM)

In the present investigation, the second-order RSM-based mathematical models for flank wear (VB), surface roughness (Ra) and lifespan (T) were developed with cutting speed (Vc), feed rate (f), and cutting time (t) as the process parameters. RSM technique is recognized as a statistical technique based on simple multiple regressions. Using this technique, the effect of two or more factors on quality criteria can be investigated and optimum values could be obtained. The results are expressed in 3D series or counter map. In the procedure of analysis, the approximation of response (Y) was proposed using the fitted second-order polynomial regression model which is commonly called the quadratic model. The quadratic model of Y can be written as follow (eq. 1):

$$Y = a_0 + \sum_{i=1}^3 a_i X_i + \sum_{i=1}^3 a_{ii} X_i^2 + \sum_{i < j} a_{ij} X_i X_j + \varepsilon \quad (1)$$

Where a_0 is constant, a_i , a_{ii} and a_{ij} represent respectively the coefficients of linear, quadratic and cross product terms. X_i reveals the coded variables that correspond to the studied machining parameters such as cutting speed (Vc), feed rate (f) and cutting time (t), and ε is a random experimental error.

The analysis of variance (ANOVA) has been applied to check the adequacy of the developed machinability models [14]. The ANOVA table consists of sum of squares and degrees of freedom. The sum of squares is performed into contributions from the polynomial model and the experimental value and was calculated by the following equation:

$$SS_{fa} = \frac{N}{N_{nfa}} \sum_{i=1}^{N_{nfa}} (\bar{y}_i - \bar{y})^2 \quad (2)$$

Where $\bar{y} = 1/N \sum_{i=1}^N y_i$ is the average of responses, y_i is the average response observed in experiments where the factor fa takes its i th level, N is the total number of experiments and N_{nfa} is the level of each factor fa .

The mean square is the ratio of sum of squares to degrees of freedom was calculated by the following equation:

$$Ms_i = \frac{SS_{fa}}{df_i} \quad (3)$$

The F-value is the ratio of mean square of regression model to the mean square of the experimental error was calculated by the following equation:

$$F_i = \frac{Ms_i}{Ms_e} \quad (4)$$

This analysis was out for a 5 % significance level, i.e., for a 95 % confidence level. The last column of the tables shows the percentage of each factor contribution (Cont. %) on the total variation, then indicating the degree of influence on the result, was calculated by the following equation:

$$Cont.\% = \frac{SS_{fa}}{SS_T} \times 100 \quad (5)$$

Table 4

Experimental results for surface roughness and flank wear

Run	Factors			Responses	
	Vc, m/min	f, mm/rev	t, min	Ra, μ m	VB, mm
1	280	0.08	4	0.56	0.025
2	280	0.08	10	0.61	0.050
3	280	0.08	16	0.74	0.100
4	280	0.11	4	0.81	0.030
5	280	0.11	10	1.17	0.074
6	280	0.11	16	1.25	0.110
7	280	0.14	4	1.32	0.045
8	280	0.14	10	1.34	0.069
9	280	0.14	16	1.35	0.110
10	330	0.08	4	0.55	0.040
11	330	0.08	10	0.62	0.115
12	330	0.08	16	0.80	0.190
13	330	0.11	4	0.79	0.060
14	330	0.11	10	1.21	0.135
15	330	0.11	16	1.60	0.170
16	330	0.14	4	1.31	0.06
17	330	0.14	10	1.47	0.185
18	330	0.14	16	1.92	0.350
19	400	0.08	4	0.80	0.050
20	400	0.08	10	1.24	0.200
21	400	0.08	16	1.99	0.410
22	400	0.11	4	0.87	0.065
23	400	0.11	10	1.55	0.290
24	400	0.11	16	2.95	0.460
25	400	0.14	4	1.16	0.070
26	400	0.14	10	1.70	0.300
27	400	0.14	16	3.20	0.510

3 Results and discussion

Table 4 and table 5 show all the values of the response factors: flank wear (VB), surface roughness (Ra) and lifespan (T), and were made with the objective of analysing the influence of the cutting speed (V_c), feed rate (f), and cutting time (t) on the total variance of the results. The surface roughness was obtained in the range of 0.55–3.2 μ m; flank wear and lifespan were obtained in the range of 0.025-0.51 mm, and 10-44 min, respectively.

Table 5
Experimental results for lifespan

Run	Factors		Response
	V_c , m/min	f , mm/rev	T, min
1	280	0.08	44
2	280	0.11	42
3	280	0.14	39
4	330	0.08	27
5	330	0.11	20
6	330	0.14	15
7	400	0.08	15
8	400	0.11	11
9	400	0.14	10

3.1. Analysis of variance

Tables 6-8 show the results of ANOVA analysis for flank wear surface roughness and lifespan. In addition, the same tables (6-8) show the degrees of freedom, sum of square, mean of square, F-value and P-value. The ration of contribution of different factors and their interactions were also presented. The main purpose was to analyse the influence of cutting speed (V_c), feed rate (f), and cutting time (t) on the total variance of the results.

From the analysis of table 6, it can be apparent seen that the cutting time (t), cutting speed (V_c), interactions ($V_c \times t$, $f \times t$) and feed rate (f) all have significant effect on the flank wear (VB). But, the effect of cutting time is the most significant factor associated for flank wear with 46.18 %. The next largest factor influencing VB is the cutting speed. Its contribution is 33.60 % to the model. The interaction ($V_c \times t$) were less significant, while ($V_c \times f$) interaction and productions (V_c^2 , f^2 , t^2) were found to be negligible.

Table 6
ANOVA for response surface quadratic model of VB

Source	df	SS	Ms	F-value	P-value	Cont. %	Remarques
Model	9	0.487673	0.054186	65.45893	< 0.0001	97.20	Significant
V_c	1	0.168587	0.168587	203.6604	< 0.0001	33.60	Significant
f	1	0.015655	0.015655	18.91225	0.0004	3.12	Significant
t	1	0.231715	0.231715	279.9219	< 0.0001	46.18	Significant
$V_c \times f$	1	0.002066	0.002066	2.495334	0.1326	0.41	Not Significant
$V_c \times t$	1	0.081335	0.081335	98.25617	< 0.0001	16.21	Significant
$f \times t$	1	0.003675	0.003675	4.439562	0.0503	0.73	Significant
V_c^2	1	8.4E-05	8.4E-05	0.101493	0.7539	0.02	Not Significant
f^2	1	0.000153	0.000153	0.185256	0.6723	0.03	Not Significant
t^2	1	6.69E-06	6.69E-06	0.008076	0.9294	0.00	Not Significant
Residual	17	0.014072	0.000828				
Total	26	0.501745					

However, table 7 shows the ANOVA table for response surface quadratic model for surface roughness (Ra). The value of “P-value” in table 6 for model is less than 0.05 which indicates that the model is significant, which is desirable as it indicates that the terms in the model have a significant effect on the response. In the same manner, the main effect of cutting time (t), feed rate factor (f), cutting speed (Vc), the interaction of cutting speed and cutting time ($Vc \times t$), and the product (Vc^2) are significant model terms. It can be seen that the cutting time (t) is the most important factor affecting Ra . Its contribution is 31.96 %. The second important factor affecting Ra is the feed rate, because its increase generates helicoid furrows, the result of tool shape and helicoid movement tool-workpiece. These furrows are deeper and broader as the feed rate increases. Its contribution is 23.25%. The next factors influencing Ra are the cutting speed, the interaction ($Vc \times t$) and the product (Vc^2). Other model terms can be said to be not significant.

Table 7ANOVA for response surface quadratic model of Ra

<i>Source</i>	<i>df</i>	<i>SS</i>	<i>Ms</i>	<i>F-Value</i>	<i>P-value</i>	<i>Cont.%</i>	<i>Remarques</i>
<i>Model</i>	9	10.51	1.17	31.75	< 0.0001	94.34	<i>Significant</i>
<i>Vc</i>	1	2.21	2.21	60.14	< 0.0001	19.84	<i>Significant</i>
<i>f</i>	1	2.59	2.59	70.52	< 0.0001	23.25	<i>Significant</i>
<i>t</i>	1	3.56	3.56	96.88	< 0.0001	31.96	<i>Significant</i>
<i>Vcxf</i>	1	1.71E-03	1.71E-03	0.046	0.8319	0.02	<i>Not Significant</i>
<i>Vcxt</i>	1	1.91	1.91	51.85	< 0.0001	17.15	<i>Significant</i>
<i>fxt</i>	1	0.094	0.094	2.55	0.129	0.84	<i>Not Significant</i>
<i>Vc^2</i>	1	0.17	0.17	4.55	0.0479	1.53	<i>Significant</i>
<i>f^2</i>	1	0.055	0.055	1.49	0.2389	0.49	<i>Not Significant</i>
<i>t^2</i>	1	0.086	0.086	2.33	0.1455	0.77	<i>Not Significant</i>
<i>Residual</i>	17	0.63	0.037				
<i>Total</i>	26	11.14					

Finally from analysis of table 8, it can be apparently seen that the cutting speed factor (Cont. \approx 88 %), the feed rate factor (Cont. \approx 5 %) and the product Vc^2 (Cont. \approx 9.9 %) have statistical significance on the lifespan (T), especially the cutting speed.

Table 8ANOVA for response surface quadratic model of T

<i>Source</i>	<i>df</i>	<i>SS</i>	<i>Ms</i>	<i>F-Value</i>	<i>P-value</i>	<i>Cont.%</i>	<i>Remarques</i>
<i>Model</i>	5	1477.928	295.5855	50.30407	0.0043	98.82	<i>Significant</i>
<i>Vc</i>	1	1320.167	1320.167	224.6719	0.0006	88.27	<i>Significant</i>
<i>f</i>	1	79.83021	79.83021	13.58586	0.0346	5.34	<i>Significant</i>
<i>Vcxf</i>	1	0.149847	0.149847	0.025502	0.8833	0.01	<i>Not Significant</i>
<i>Vc^2</i>	1	147.8914	147.8914	25.16883	0.0153	9.89	<i>Significant</i>
<i>f^2</i>	1	0.888889	0.888889	0.151275	0.7233	0.06	<i>Not Significant</i>
<i>Residual</i>	3	17.62793	5.875977				
<i>Total</i>	8	1495.556					

To better view the results of the analysis of variance, a *Pareto* graph is built (Fig. 2 a, b, and c). This figure ranks the cutting parameters and their interactions of their growing influence on the flank wear (*VB*), surface roughness (*Ra*) and lifespan (*T*). Effects are standardized (F-value) for a better comparison. Standardized values in this figure are obtained by dividing the mean square of each factor by the mean square of the error. The more standardized the effect, the higher the factor considered influence. If the F-table values are greater than 4.45 for *VB* and *Ra*; and greater than 10.13 for lifespan, the effects are significant. By cons, if the values of F-value are less than (4.45; 10.13) the effects are not significant. The confidence interval chosen is 95 %

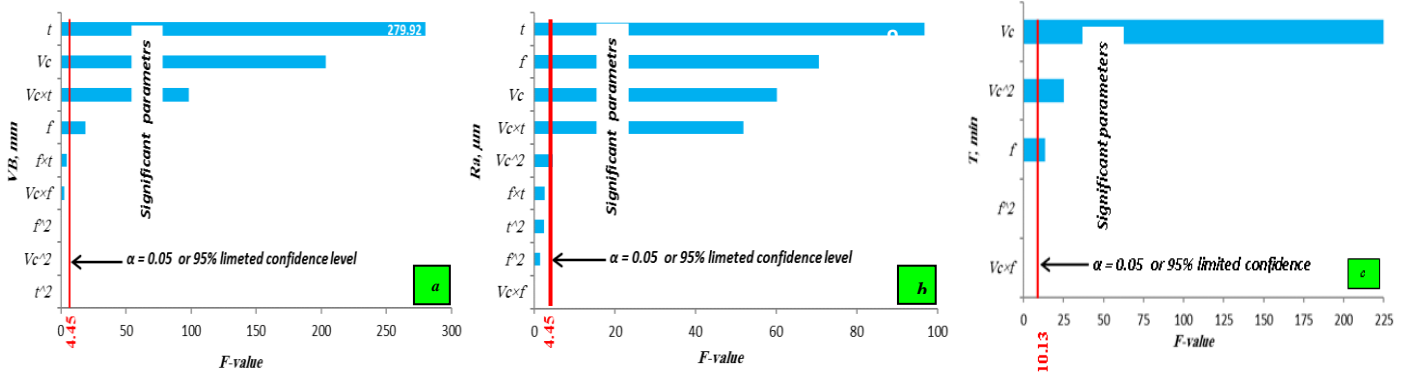


Figure 2 Pareto graphs of: a) flank wear, b) surface roughness and c) lifespan

3.2. Regression equation for various responses

The functional relationship between the dependent variables (*VB*, *Ra* and *T*) and the investigated independent variables (cutting speed, feed rate and cutting time) were represented joined with the correlation coefficients R^2 which proves the regression accuracy. The different quadratic models obtained from statistical analysis can be used to predict the flank wear, surface roughness and lifespan according to the studied factors.

The models and its determination coefficients obtained for different cutting phenomena are presented in (eq.6, eq.7 and eq.8) respectively to (flank wear, surface roughness and lifespan).

$$VB = 0.65 - 0.0021Vc - 3.68f - 0.069t + 1.074 \cdot 10^{-6}Vc^2 + 0.0072 Vc \times f + 0.00022Vc \times t + 5.61f \times f + 0.097f \times t + 2.93 \cdot 10^{-5} t^2$$

$$R^2 = 97.20\%$$

$$Ra = 5.68 - 0.037 Vc + 33.37f - 0.421 t + 4.79 \cdot 10^{-5}Vc^2 - 6.6 \cdot 10^{-3}Vc \times f + 0.0011Vc \times t - 106.173 f^2 + 0.49f \times t + 0.0033 t^2$$

$$R^2 = 94.39\%$$

$$T = 413,26 - 1,94Vc - 321,22 f + 0,0024Vc^2 + 0,11Vc \times f + 740,741f^2$$

$$R^2 = 98.82\%$$

In order to reduce the models, only the significant parameters will be conserved.

$$VB = 0.19 - 6.59 \cdot 10^{-4}Vc - 0.011f - 0.069t + 2.27 \cdot 10^{-4}Vc \times t + 0.097222f \times t$$

$$R^2 = 96.73\%$$

$$Ra = 6.35 - 0.037 Vc + 12.703f - 0.3t + 1.102 \cdot 10^{-3}Vc \times t + 4.79 \cdot 10^{-5}Vc^2$$

$$R^2 = 92.27\%$$

$$T = 400.77 - 1.92Vc - 122.22 f + 2.47 \cdot 10^{-3}Vc^2$$

$$R^2 = 98.75\%$$

The above models can be used to predict flank wear, surface roughness and lifespan at the particular design points. The differences between measured and predicted responses are illustrated in figures 3, 4, and 5. These figures indicate that the quadratic models are capable to representing the system under the given experimental domain.

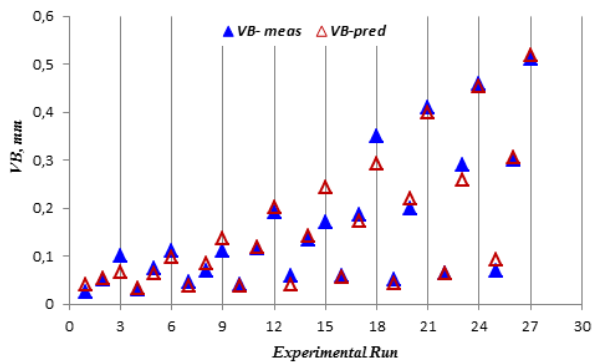


Figure 3 Comparison between measured and predicted values for flank wear

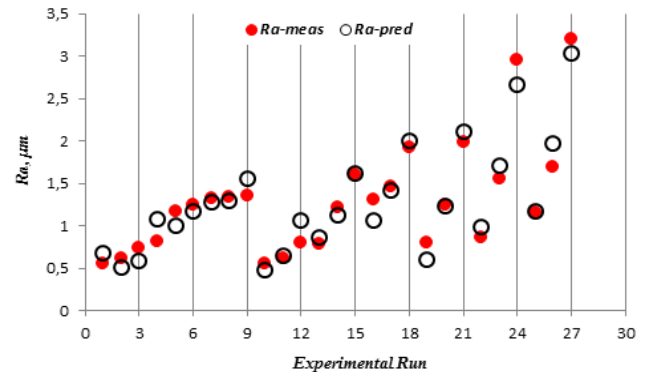


Figure 4 Comparison between measured and predicted values for surface roughness

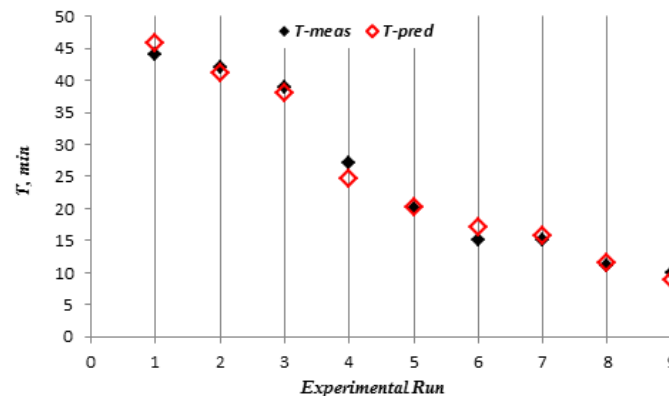


Figure 5 Comparison between measured and predicted values for lifespan

The Anderson–Darling test and normal probability plots of predicted response for: surface roughness, flank wear and tool lifespan respectively, are presented in figures 6 (a, b, c). The data closely follows the straight line. The null hypothesis is that the data distribution law is normal and the alternative hypothesis is that it is non-normal. Using the P-value which is greater than alpha of 0.05 (level of significance), the null hypothesis cannot be rejected (i.e., the data don't follow a normal distribution). It implies that the models proposed are adequate.

3.3. Mathematical models validation

The analysis of variance (ANOVA) was used to check the adequacy of developed models for a given confidence interval. The ANOVA table consists of sum of squares and degrees of freedom. In order to perform an ANOVA, the sum of squares is usually completed into contributions from regression model and residual error. As for this technique, if the calculated value of F-ratio of model is more than the standard tabulated value of table (F-table) for a given confidence interval, then the model is adequate within the confidence limit [15, 16 and 17]. The adequacy of developed

mathematical models is presented in tables 9. The model accuracy (Δ) is commonly given by the following equation [18]:

$$\Delta = \frac{100}{n} \sum_{i=1}^n \left| \frac{y_{i, \text{expt}} - y_{i, \text{pred}}}{y_{i, \text{pred}}} \right| \quad (12)$$

Where $y_{i, \text{expt}}$ is the measured value of response corresponding to i^{th} trial, $y_{i, \text{pred}}$ is the predicted value of response corresponding to i^{th} trial and n is the number of trials. Equations (9, 10 and 11) are used to test the accuracy of the models using the experimental data. The prediction errors of these models are illustrated in Table 10 together with determination coefficients. It is concluded that the correlations are valid and can be used for predictions when turning AISI304 stainless steel.

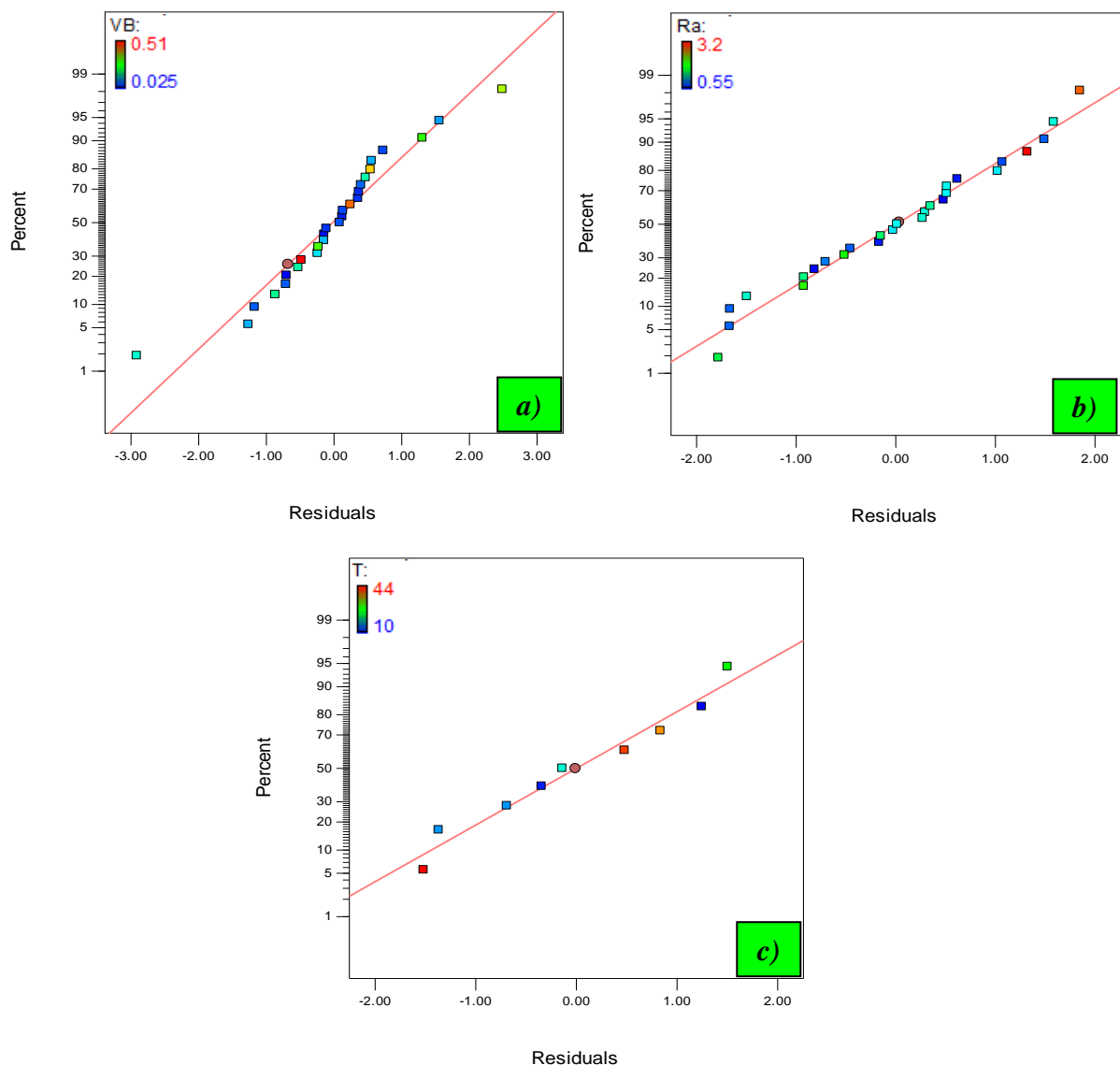


Figure 6 Normal probability plots of predicted response for:
a) flank wear ,**b)** surface roughness and **c)** lifespan

Table. 9ANOVA analysis for VB , Ra and T

Responses	SS		D. f		Ms		F-test	F-table	P-value
	M	R	M	R	M	R			
VB	0.48	0.014	9	17	0.054	0.0008	65.45	2.49	< 0.0001
Ra	10.51	0.63	9	17	1.17	0.037	31.75	2.49	< 0.0001
T	1477.9	17.62	5	3	259.58	5.87	50.3	9.01	0.0043

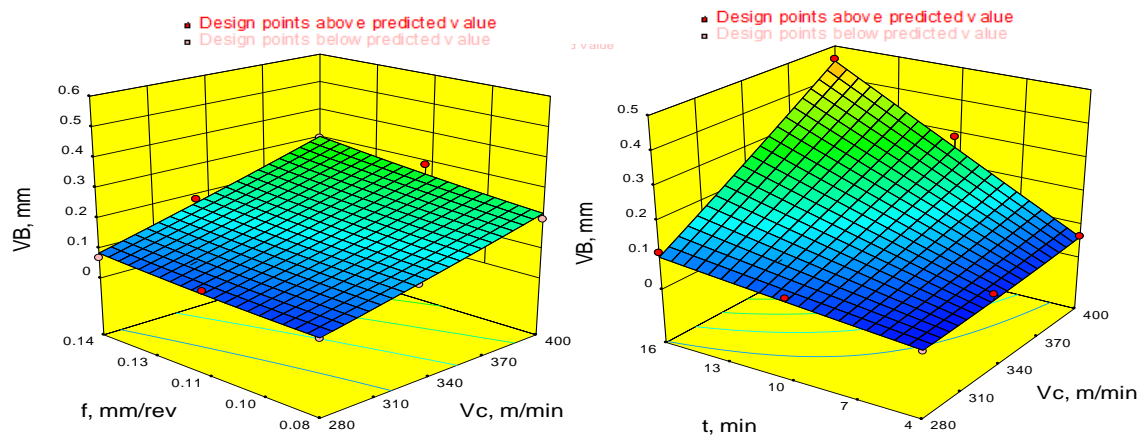
M: model; *R*:residual**Table. 10**Percent prediction error of the experimental data and R^2 values of VB , Ra and T models

Responses	% Prediction error of the experimental data	R^2 (%) Values of models
VB	14.31	96.73
Ra	11.51	92.27
T	6.14	98.75

3.4 Responses surface analysis

3.4.1 Flank wear

Figure 7 illustrates the evolution of the flank wear according to the cutting speed, cutting time and feed rate. It is found that tool wear increases with increasing effects of both cutting time and speed. It can be concluded that the cutting time exhibits maximum influence on flank wear. The maximum value of flank wear is found with height level of cutting time and cutting speed.

**Figure 7** Effect of cutting speed, feed rate and cutting time on flank wear

3.4.2 Workpiece surface roughness

The estimated response surface for the surface roughness in relation to the cutting parameters (Vc , f and t) presented in figure 8, it can be seen that the cutting speed had a significant influence on machined surface roughness. A high values of surface roughness noted in small value of cutting speed that can be explained by the presence of built up edge (fig. 9) on the surface due to the high ductility of austenitic stainless steel.

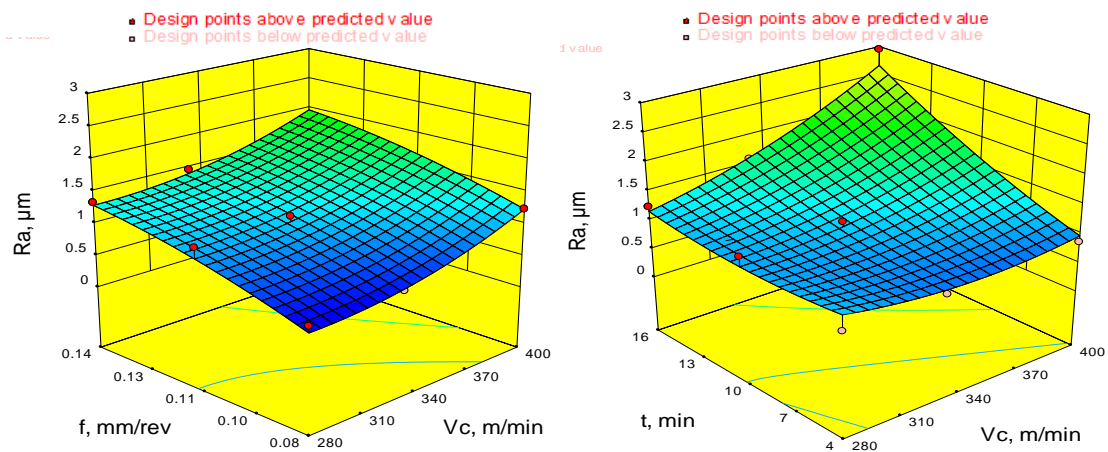


Figure 8 Effect of cutting speed, feed rate and cutting time on surface roughness

With the increasing of cutting speed the surface roughness values decrease until a minimum value reached beyond which they increase. The decrease in surface roughness when increasing of cutting speed to 340 m/min can be explained by the presence of micro-welds on machined surface due to high heat at cutting zone and the height of built-up edge which lead to the breaking of BUE and carried away on the machined surface as seen in figure 9. Further, increasing the cutting speed causes an increase in surface roughness because the cutting tool nose wear increases causing the poor surface finish [19]. In the other hand, the roughness (Ra) tends to increase, considerably with increase in feed rate (f) and cutting time (t).

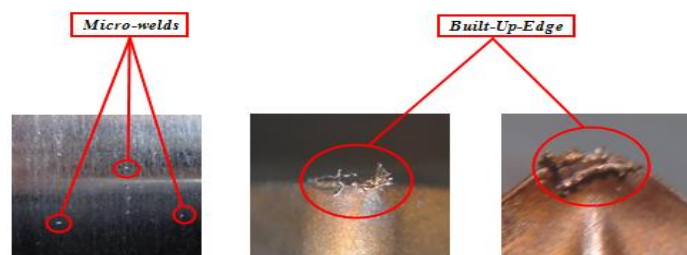


Figure 9 Micro-Weld on machined surface and Built-Up Edge on cutting insert

3.4.3 Lifespan

The effect of feed rate (f) and cutting speed (Vc) on the tool life (T) is shown in figure 10. This figure displays that the value of tool life (T) decrease with the increase of cutting speed and feed rate. The decrease is approximately 77.27% of T .

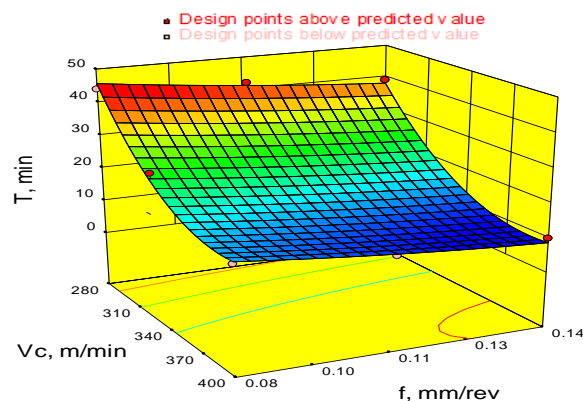


Figure 10 Effect of cutting speed and feed rate on tool lifespan

3.5 Micrographs for flank wear VB of the GC2015 tool

For the considered regime ($V_c = 280$ m/min, $ap = 0.15$ mm and $f = 0.08$ mm/rev), flank wear VB of the coated carbide tool GC2015 spreads regularly. Figure 11 shows the micrographs for VB of GC2015 insert, its life time is 44 min.

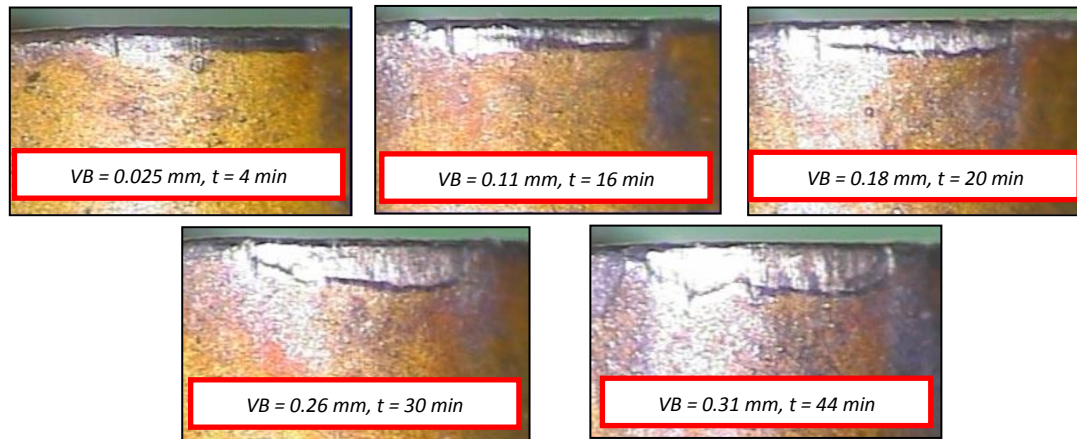


Figure 11 Micrographs for VB of GC2015 at $ap = 0.15$ mm; $f = 0.08$ mm/rev and $V_c = 280$ m/min

4 Optimization of responses

According to Bouzid et al. [20], desirability function is not a direct optimisation method. It has been exploited to optimise multiple response factors (VB , Ra and T). The desirability function is a decision support tool to identify process parameters that are resulting in near-optimum settings for process responses. The optimisation module searches for a combination of factor levels that simultaneously satisfies the requirements placed on each of the responses and factors in an attempt to establish the appropriate model. During the optimisation process, the aim was to find the optimal values of machining parameters in order to produce the lowest flank wear, surface roughness (VB and Ra) and the highest lifespan (T).

The constraints used during the optimisation process are summarised in table 11. The optimal solutions are reported in table 12 and table 13 in order of decreasing desirability level.

Table 11 Constraints for optimization of machining parameters

<i>Condition</i>	<i>Goal</i>	<i>Lower limit</i>	<i>Upper limit</i>
Cutting speed V_c (m/min)	In range	280	400
Feed rate f (mm/rev)	In range	0.08	0.14
Cutting time t (min)	In range	4	16
Flank wear VB (mm)	Minimize	0.025	0.3
Arithmetic mean roughness Ra (μ m)	Minimize	0.55	3.2
Lifespan T (min)	Maximize	10	44

Table 12 shows the optimization results corresponding to lower values of both flank wear (VB) and surface roughness (Ra). Optimal cutting parameters found to be cutting speed of (317-325 m/min), feed rate of (0.08 mm/rev), and cutting time of (4min). The optimized parameters are surface roughness $Ra = 0.54\mu$ m and flank wear $VB=0.036$ mm. With a Composite Desirability = 0.978 (figure 11).

Table 12

Response optimization for surface roughness and flank wear

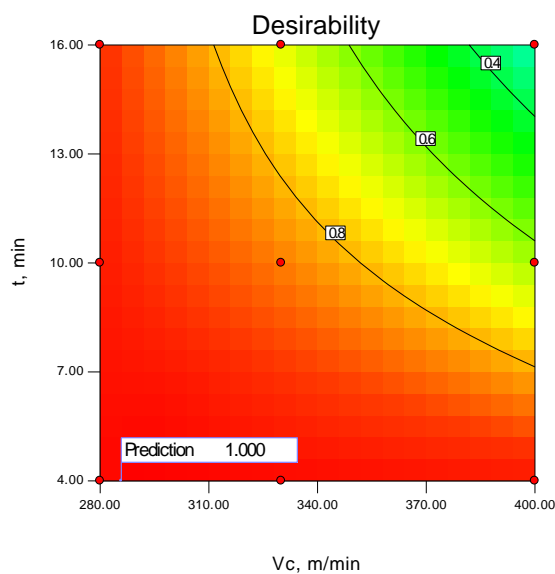
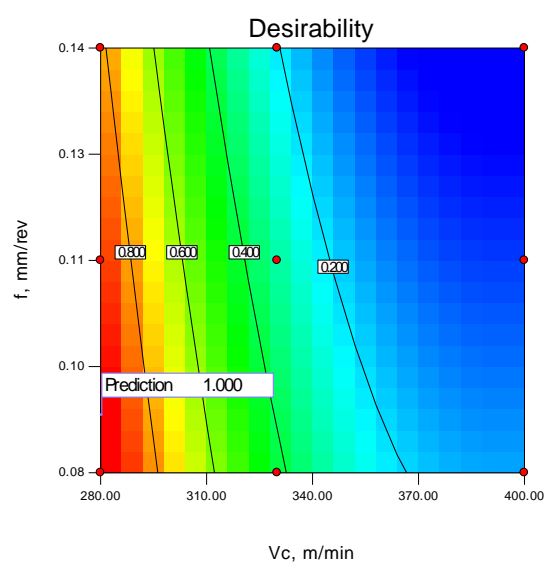
<i>Solution N°</i>	<i>Vc (m/min)</i>	<i>f (mm/rev)</i>	<i>t (min)</i>	<i>Ra (µm)</i>	<i>VB (mm)</i>	<i>Desirability</i>	<i>Remarks</i>
1	319.28	0.08	4.00	0.549918	0.0369099	0.978	<i>Selected</i>
2	317.80	0.08	4.00	0.549864	0.0369145	0.978	
3	318.61	0.08	4.00	0.549912	0.036917	0.978	
4	320.43	0.08	4.00	0.540874	0.0369382	0.978	
5	321.18	0.08	4.00	0.533516	0.0369609	0.978	
6	324.46	0.08	4.00	0.535949	0.0369873	0.978	
7	318.94	0.08	4.00	0.526607	0.0369981	0.978	
8	325.51	0.08	4.00	0.548811	0.0370093	0.978	

Table 13

Response optimization for lifespan

<i>Solution N°</i>	<i>Vc (m/min)</i>	<i>f (mm/rev)</i>	<i>T (min)</i>	<i>Desirability</i>	<i>Remarks</i>
1	280.66	0.09	44.5209	1.000	<i>Selected</i>
2	280.52	0.09	44.2427	1.000	
3	280.33	0.09	44.204	1.000	
4	280.00	0.08	45.7375	1.000	
5	280.15	0.08	45.2762	1.000	
6	281.28	0.08	44.8579	1.000	
7	280.22	0.08	45.3091	1.000	
8	280.11	0.09	44.0664	1.000	

Table 13 shows the RSM optimization results for lifespan (T). The optimum cutting parameters obtained in table 8 for cutting speed of (280.66 m/min) and feed rate of (0.08 to 0.09 mm/rev). The optimized lifespan is $T = (44.2 \text{ to } 45.73 \text{ min})$. With a Composite Desirability = 1 (figure 12).

**Figure 12** Composite desirability for flank wear and surface roughness**Figure 13** Composite desirability for lifespan

5 Conclusion

In this paper, the application of RSM for the turning of AISI 304 stainless steel with CVD coated carbide tool was presented. Mathematical models of flank wear (VB), surface roughness (Ra) and lifespan (T) evolutions according to the influence of machining parameters were investigated and optimal cutting parameters are determined. Conclusions of this research can be resumed are the following points:

1) The flank wear of CVD coated carbide tool increased with cutting speed and cutting time. The present study shows that a higher tool wear rate is noted at cutting speed 400 m/min and cutting time of 16 min.

2) The flank wear is influenced principally by the cutting time, cutting speed and the interaction effect of cutting speed/cutting time with a contribution of 46.18%, 33.6% and 16.21%, respectively.

3) The cutting time has a greater influence on the surface roughness (31.96%) followed by feed rate (23.25%), cutting speed (19.84%) and the interaction cutting speed/cutting time (17.15%).

4) Cutting speed influences lifespan (T) of GC2015 more significantly than the feed rate.

5) The tool life of the coated carbide GC2015 is 44 min.

6) The statistical models deduced define the degree of influence of each cutting regime element on flank wear and surface roughness. They can also be used for optimization of the cutting process.

7) The ranges of best cutting conditions adopted, are: $V_c = (317 \text{ to } 325) \text{ m/min}$, $f = (0.08) \text{ mm/rev}$ and $t = (4) \text{ min}$ for flank wear and surface roughness, and $V_c = 280.66 \text{ m/min}$, $f = (0.8 \text{ to } 0.9) \text{ mm/rev}$ for lifespan.

Nomenclature

V_c	cutting speed (m/min)	RSM	response surface methodology
f	feed rate (mm/rev)	ANOVA	analysis of variance
t	cutting time (min)	df	degrees of freedom
VB	flank wear (mm)	SS	sequential sum of squares
Ra	arithmetic mean roughness (μm)	MS	adjusted mean squares
T	lifespan	Cont. %	contribution ratio (%)
b_{ii}	quadratic terms	α	clearance angle ($^\circ$)
b_j	coefficients of linear terms	χ_r	major cutting edge angle ($^\circ$)
b_{ij}	cross-product terms	γ	rake angle ($^\circ$)
R^2	determination coefficient	λ	cutting edge inclination angle ($^\circ$)
SS_{fa}	sum of square of the factor fa	SS_T	total sum of square
P-value	probability value		

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