Modeling and Optimization of Hard Turning Operation on 41Cr4 Alloy Steel Using Response Surface Methodology

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Abstract: Product quality, productivity and organizational goodwill are often the major concern of every production or manufacturing unit. These criteria, more especially product quality, cannot readily and effectively be met through dependence on the skills of an operator. Hence, the need for optimization in order to identify the best process condition, derived from parametric combinations of process variables, for the manufacturing process. The work presented concerns an aspect of a series of hard turning experiments on 41Cr4 alloy structural steel conducted to model, predict and optimize the machining induced vibration, and the surface roughness as functions of the cutting speed, feed rate, and the tool nose radius. The response surface methodology, based on the central composite design of experiment is employed in the study, and analysis of the generated data performed with the aid of Design expert 9 software. A quadratic regression model was suggested as best fits for both the machining induced vibration and surface roughness data. These were confirmed by analyses of variance, which also revealed the tool nose radius and cutting speed, as well as the feed rate and cutting speed to be important factors that determine changes in the machining induced vibration and surface roughness, respectively. The optimum setting of the tool nose radius at 1.72301 mm, feed rate at 0.15 mm/rev, and the cutting speed at 311.075 rev/min minimized the machining induced vibration to a value of 0.08 mm/min² and the surface roughness to a value of 4.74 μmm.

Keywords: Tool Nose Radius, Feed Rate, Cutting Speed, Machining Induced Vibration, Surface Roughness, Turning Experiment, Response Surface Methodology

1. Introduction

The major lathe machine operations include turning, facing, threading, and boring. However, with attachments, or any other acceptable means of improvisation, many other operations can be possible with lathe machines. These operations essentially involve surface generation with single point cutting tools. The quality of the generated surfaces is an important factor in industrial production or manufacture of machined parts. It is a function of the machining condition, and cutting tool and work-piece material and geometry. Turning process, which is of interest in this work, involves externally cylindrical surface generation. This is often achieved when a translating single point cutting tool encounters external surface of a rotating cylindrical work-

piece under optimal machining conditions and other factors attributable to the used cutting tool and work-piece.

In the past, industry relied mainly on the skill and experience of operators to achieve optimal setting of work, and hence, the desired quality and performance characteristics. Later other traditional or conventional techniques [1] [2], like Taylor's tool life equation, and a number of analytical and experimental techniques for optimization evolved, and subsequently, were used to tackle the optimization problem so far with moderate level of success. Presently, attention on the same issue has shifted to the use of more accurate modern or non-conventional techniques [1] [2]. These techniques includes the fuzzy logic, scatter search technique, genetic algorithm, Taguchi technique, simulated annealing, and the response surface methodology. To some extent these techniques have been

used in optimization of the quality and performance characteristics in the turning process. However, more research efforts are required, as new materials and process technology evolve, to ensure that industry have adequate information about products, processes and means of manufacture, and to ensure product quality, productivity and organizational goodwill are given due attention.

The purpose of this work is to model, predict and optimize the machining induced vibration (V_f) and surface roughness (R_a) as functions of the tool nose radius (A), feed rate (B) and cutting speed (C) using data generated from hard turning of 41Cr4 alloy structural steel on a conventional lathe machine with standard cutting tool. The response surface methodology (RSM), based on the central composite (CC) design of experiment (DOE) was used, and the data generated from the turning experiment were analyzed using the Design Expert 9.0.6.2 software.

The work was supported by the works of Ozcarar and Kasapoglu [3], Abhang and Hameedullah [4], Sahoo [5], Abhang and Hameedullah [6], Sastry and Devi [7], Srinivasan et al [8], Ramudu and Sastry [9], Aruna and Dhanalaksmi [10], Chomsamutr and Jongprasithporn [11], Abhang and Hameedullah [12], Manu et al [13], Makadia and Nanavati [14], Kannan et al [15], Phate and Tatwawadi [16], Bhuiyan and Ahmed [17], Manohar et al [18], Thiyaagu et al [19], Saini and Parkash [20], Saini et al [21], Soni et al [22], Shunmugesh et al [23], Kumar [24], Sastry et al [25], Revankar et al [26], Mahajan et al [27], Shihab et al [28], Gupta and Kohli [29], Khan et al [30], Devkumar et al [31], Devi et al [32], Rajpoot et al [33], Khidhir et al [34], Agrawal et al [35], Ranganath et al [36], and Chandra and Prasad [37]. The response surface methodology (RSM), as used in these works, was based on a variety of approach on design of experiment, and the generated data analyzed in a variety of software environment. A variety of work-piece materials, cutting tools, lathe machines, and parameter measurement instruments were considered. A variety of process variables and constants, and performance variables were investigated. However, results obtained from surface roughness data are in close semblance. Besides, the study is supported by the work of Kassab and Khoshnaw [38], Han et al [39], Cahuc et al [40], Delijaicov et al [41], Rogov and siamak [42], [43], which considered essentially the machining induced vibration of either the cutting tool or work-piece as the response variable.

2. Materials, Equipment and Method

2.1. Work-Piece

Chemical analysis and mechanical tests were conducted on the selected work-piece material using the laboratory at Standards Organization of Nigeria, Emene, Enugu and the observed chemical composition and mechanical properties recorded as given Tables 1 and 2. The test results revealed work-piece material to be 41Cr4 quenched and tempered

(QT) alloy special steel, with material number as 1.7035. Its equivalent grades were found to be SAE-AISI 5140, BS 530M40, EN 10083-3 or EN18, and VC140. In comparison, they have no semblance with those previously investigated. A technical report by FUHONG on special steels claims 41Cr4 to be one of the most widely used alloy steel, more specifically, for driving elements like crankshafts, front vehicle axles, axle journals and steering components. It is also seen as having good overall mechanical properties, low temperature impact toughness and hardenability after quenching and tempering (QT) heat treatment; and higher fatigue strength after oil cooling. The machinability of this material is good when subjected to normalizing and QT conditions, but its weldability is not good, and as a result, cannot easily be processed when subjected to welding conditions. For the turning experiment, specimen work-piece of this material, given in Fig. 1, are round bars having dimensions of diameter, 25 mm, and length, 150 mm.

Table 1. Chemical composition of 41Cr4 alloy special steel.

Quality of material	Type of material	Average elements %			
		Carbon (C)	Silicon (Si)	Manganese (Mn)	Chromium (Cr)
Quenched and Tempered Steel	41Cr4	0.40	0.25	0.65	1.00

Table 2. Mechanical properties of 41Cr4 alloy special steel.

Sample ID	Diameter (mm)	Area (mm ²)	BHN	Peak load (kN)	U _{ts} N/mm ²
Solid, Round	10.00	78.55	278.48	70.92	902.83

Figure 1. Samples of 41Cr4 Alloy Steel Bars.

2.2. Processing Equipment

An engine lathe of the type YUCY6240B, with serial number, 2008031074 (Fig. 2a), and a carbide cutting tool of the type F30 (Fig. 2b) were used in the turning experiment. The overall dimensions of the tool insert is 25 mm x 25 mm x 12.5 mm. Its back rake angle is 10°, side rake angle is 12°, side relief angle is 5° and side cutting edge angle is 15°.

(a)

(b)

Figure 2. (a) Conventional lathe machine, YUCY6240B; (b) Cutting tool with carbide insert, F30.

2.3. Process Variables

The tool nose radius (A), feed rate (B) and cutting speed (C) are the selected process variables. Others were kept constant within experimental limits. The tool nose radius (A) [mm] is the radius of the tool at its cutting point. Feed rate (B) [mm/rev] is the speed of the cutting tool relative to that of the work-piece as the tool takes a cut along the axis of the work-piece. The cutting speed (C) [rev/min] is the rotational speed of the lathe machine spindle or the work-piece. The extent to which these variables influence the surface roughness (R_a) and machining induced vibration (V_i), is being investigated. To improve on quality of the machined part, the process variables A, B and C can be set within limits (Table 3) as to minimize R_a and V_i .

Table 3. Levels of the input variables.

S/N	Parameters	Notation	Unit	Levels		
				Low	Medium	High
1	Tool Nose Radius	A	[mm]	0	1	2
2	Feed rate	B	[mm/rev]	0.15	0.225	0.30
3	Cutting Speed	C	[rev per min]	260	330	400

(a)

(b)

Figure 3. (a) Surface roughness tester, ISR-16; (b) Vibration meter with transducer, 908 BE.

2.4. Response Variables

The surface roughness (R_a) and machining induced vibration (V_i) are the selected response variables.

2.4.1. Surface Roughness

The surface roughness (R_a), as a measure of surface texture [2], is the vertical deviations of a real surface from its ideal form. A large deviation is taken as a rough surface, while a small deviation is taken as a smooth surface. Thus, surface roughness is seen as the high frequency, short wavelength component of a measured surface, which determines how a real object will interact with its environment. Rough surfaces wear faster and have higher coefficient of friction than smooth surfaces. Again, roughness of a surface [micron, μm , or μmm] may form nucleation sites for cracks or corrosion, promote adhesion, and may be very expensive to control in manufacturing. In this study, an inside surface roughness tester, ISR-16, such as given in Fig. 3a was used to undertake measurement of the surface roughness. It was taken at three different positions located at 120° on the surface and about the axis of the work-pieces. The surface texture of the turned surface is taken to be the average of these values. Surface roughness (R_a) [μm] is the center line average roughness [5], also known as, the arithmetic deviation of the surface height from the mean line through the profile, which separates the profile above and below it by equal area.

2.4.2. Machining Induced Vibration

The four different ways vibrations may occur, during turning and allied lathe operations, include (a) sudden clash of a tool against a work-piece, (b) irregular tissues of the work-piece, (c) regular excitation due to asymmetric torque, and (d) due to bearing defects. The machining induced vibration is related to a sudden clash of a tool against a work-piece, also known as self-excited vibration. It occurs at the cutting zone due to interaction of the cutting tool, chips, and the work-piece. It is referred to as chatter [38], [39], [40], especially, when it is excessive. As chatter it can produce (a) a defective machined surface, and (b) an excessive wear and breakage of the cutting tool. It influences the surface roughness of machined components significantly [41], [42], [43]. Essentially, machining induced vibration cannot be manipulated or controlled.

However, it can be measured, and therefore, may be treated as a response variable, in the form of an acceleration amplitude [m/min²]. A vibration meter with transducer, type 908 BE (Fig. 3b) is selected for its measurement. The level of tool vibration was determined by a vertical data of a transducer mounted near to the tip and connected to the vibration meter. The amplitude of displacement and velocity of the point on the cutting tool constituted the data for each sample. The relation between the displacement, velocity and acceleration was thereafter used to calculate the amplitude of acceleration.

2.5. Design of Experiment and Method of Data Analysis

Like most techniques of design of experiment, RSM attempts to minimize the number of runs or trials, optimize values of parameters, assess experimental error, make qualitative estimation of parameters, and to make inference regarding the effect of parameters on the characteristics of a process [1]. For this reasons, RSM, based on CC-DOE, was selected. Therefore, it is used in this work to model, predict and optimize R_a and V_i as functions of the process variables, A, B and C. As a mathematical and statistical technique, it is developed for the treatment of problems involving a response of interest as a function of several variables [5]. It is one of the ways machining process modeling and analysis can be achieved to facilitate its optimization. Its application requires machining response Y to be defined as: $Y = \varphi(x_1, x_2, \dots, x_i) \pm e$, where $\varphi(x_1, x_2, \dots, x_i)$ is the response surface function in the form of a polynomial model, x_i are the process variables and e is the residual or experimental error. The second order polynomial or quadratic model may, therefore, be written as:

$$\begin{aligned} \varphi &= \varphi(x_1, x_2, \dots, x_k) \\ &= (Y \pm e) \\ &= b_0 + \sum_{i=1}^k b_i x_i + \sum_{i=1}^k b_{ii} x_i^2 + \sum_{i=1}^k \sum_{j=1}^k b_{ij} x_i x_j \end{aligned} \quad (1)$$

Equation (1) is a multiple regression model. In this form, it has constant, linear, square and cross-product terms. It can, satisfactorily, be used to correlate dependent variables, φ_j , with independent variables, x_i . A number of techniques for DOE are available for use to estimate the coefficients of the regression models. The CC was selected for the design of the turning experiment. Analysis of variance (ANOVA) was used to validate the developed models, and also, to predict the effect of selected factors A, B and C on the response characteristics, V_i and R_a . Optimization of the coded and actual response functions, $V_i(A, B, C)$ and $R_a(A, B, C)$, subject to constraints as determined by the limits of the factors A, B and C, was performed as appropriate using standard optimization technique. The RSM was implemented in the Design Expert 9 software version 9.0 6.2 environment.

2.6. Procedure of Turning Experiment

In the setup for turning experiment shown in Fig. 4, twenty-seven (27) specimen work-piece of 41Cr4 alloy steel round bars (Fig. 1) were turned on the conventional lathe (Fig. 2a) with a carbide tool insert (Fig. 2b). The run order as generated from Design Expert 9 software based on CC-DOE is given in Table 4. Measurements of V_i data were taken three times with a vibration transducer (Fig. 3b) placed on the tool post near the cutting zone. The data was transmitted to the vibration meter (Fig. 3b), and read out as displacement and velocity. The average cutting tool acceleration was determined from the general relations between displacement, velocity and acceleration. Measurements of R_a data were also taken at three (3) different locations, 120° from each other, on the machined surface using a surface roughness tester (Fig. 3a) and the average values were recorded. The measured V_i and R_a are given in Table 4.

(a)

(b)

Figure 4. Setup for the turning experiment.

Table 4. Data generated from the turning experiment.

Standard	Run	A	B	C	V_i	R_a
		Tool Nose Radius [mm]	Feed Rate [mm per rev]	Cutting Speed [rev per min]	Acceleration Amplitude [mm per min square]	Surface Roughness [micro mm]
1	17	0	0.15	260	0.13	12.857
2	21	1	0.15	260	0.15	5.602
3	26	2	0.15	260	0.13	5.790
4	19	0	0.225	260	0.23	13.710
5	9	1	0.225	260	0.30	6.840
6	12	2	0.225	260	0.24	7.524
7	6	0	0.3	260	0.16	14.193
8	23	1	0.3	260	0.20	9.184
9	14	2	0.3	260	0.24	9.250
10	3	0	0.15	330	0.17	8.213
11	5	1	0.15	330	0.15	4.590
12	22	2	0.15	330	0.05	6.292
13	16	0	0.225	330	0.21	6.895
14	7	1	0.225	330	0.19	5.115
15	8	2	0.225	330	0.14	7.149
16	27	0	0.3	330	0.09	8.110
17	2	1	0.3	330	0.16	6.342
18	15	2	0.3	330	0.12	11.080
19	18	0	0.15	400	0.33	4.839
20	20	1	0.15	400	0.25	5.320
21	24	2	0.15	400	0.14	10.300
22	25	0	0.225	400	0.38	5.870
23	11	1	0.225	400	0.33	5.093
24	4	2	0.225	400	0.22	12.903
25	1	0	0.3	400	0.24	6.137
26	10	1	0.3	400	0.19	8.418
27	13	2	0.3	400	0.12	14.760

3. Results and Discussion

Table IV shows the design layout for the turning experiment conducted as well as the response data generated. The experiment was conducted under a controlled environment to minimize error. The outcome of data analysis in the environment of the Design Expert software, version 9.0.6.2, are presented and discussed as follows:

3.1. Machining Induced Vibration Data

Table 5 shows that a quadratic model is suggested for the machining induced vibration data, with its accuracy comparatively predicted by the standard deviation of 0.019 and PRESS of 0.013, and also, by the R-square of 0.9622, adjusted R-square of 0.9421 and predicted R-square of 0.9159. Table 6 confirms the significance of the model, and

its capability for accurate prediction of V_i within the selected limits. The significant model terms are A, C, A^2 , B^2 , C^2 , AB, AC and BC. They are good predictors of the machining induce vibration (V_i). The dominance of the influence of the linear terms on V_i begins with A, followed by C, and then, B. That of the square terms on V_i starts with B^2 , followed by C^2 , and then A^2 . Also that of the cross-products terms on V_i emanates with AC followed by BC, and then, AB. Table 7, showed that the predicted R-square of 0.9159 is in reasonable agreement with the adjusted R-square of 0.9421, since the difference of 0.0262 is less than 0.2. The adequacy precision of 27.708, greater than 4, is a desirable signal to noise ratio. This indicates that there is adequate signal, and that this model can be used to navigate the design space. The models for the machining induced vibration (V_i), given in terms of the coded and actual factors A, B and C, respectively, are as follows:

$$V_i = 0.21 - 0.03A + 0.0011B + 0.023C + 0.025AB - 0.047AC - 0.03BC - 0.028A^2 - 0.081B^2 + 0.079C^2 \quad (2)$$

$$V_i = 0.55768 + 0.17056A + 8.05608B - 0.00834C + 0.33333AB - 0.00067AC - 0.00571BC - 0.02778A^2 - 14.41975B^2 + 0.000016C^2 \quad (3)$$

Figure 5a shows that the predicted V_i data fits well with the actual data. Figure 5b revealed the predicted V_i to have nonlinear relationships with the tool nose radius (A), feed rate (B), and the cutting speed (C). In terms of significance, the effect of A and C on V_i is more at low and high levels of their values, when compared to that of B. V_i decreased

continuously with increase in A. It increased with increase in B up to the reference point, and then decreased. It also decrease with increase in C to the reference point, and then, increased. The implication of the behavior is that V_i is minimized when A is set at higher level of its values and B set at either lower or higher level of its values, while C is set

at the reference point. These behaviors can also be seen in the contour and response surface plots given in Figs 6 to 8. It can as well be attributed to the observed interaction between process variables, A, B, and C.

Table 5. Model summary statistics.

Source	Standard. Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	0.076	0.1648	0.0559	-0.1549	0.18	
2FI	0.066	0.4463	0.2802	0.1517	0.13	
Quadratic	0.019	0.9622	0.9421	0.9159	0.013	Suggested
Cubic	0.023	0.9668	0.9137	0.7871	0.034	Aliased

Table 6. ANOVA for response surface quadratic model for acceleration amplitude.

Source	Sum of Squares	Degree of Freedom	Mean Square	F Value	p-value Prob > F	
Model	0.15	9	0.017	48.03	< 0.0001	significant
A-Tool Nose Radius	0.016	1	0.016	46.10	< 0.0001	
B-Feed Rate	2.222E-005	1	2.222E-005	0.063	0.8045	
C-Cutting Speed	9.800E-003	1	9.800E-003	27.89	< 0.0001	
AB	7.500E-003	1	7.500E-003	21.34	0.0002	
AC	0.026	1	0.026	74.37	< 0.0001	
BC	0.011	1	0.011	30.73	< 0.0001	
A^2	4.630E-003	1	4.630E-003	13.17	0.0021	
B^2	0.039	1	0.039	112.33	< 0.0001	
C^2	0.037	1	0.037	106.26	< 0.0001	
Residual	5.974E-003	17	3.514E-004			
Cor Total	0.16	26				

Table 7. Quadratic model statistics.

Standard Deviation	0.019	R-Squared	0.9622
Mean	0.19	Adjusted R-Squared	0.9421
C.V. %	9.62	Predicted R-Squared	0.9159
PRESS	0.013	Adequate Precision	27.708

Predicted vs. Actual

Figure 5. Predicted vs actual, and perturbation plots for V_i .

Figure 6. Contour and response surface plots of V_i against A and B with C set at 330 rev per min.

Figure 7. Contour and response surface plots of V_i against A and C with B set at 0.225 mm/rev.

Figure 8. (a) Contour and response surface plots of V_i against B and C with A set at 1 mm.

3.2. Surface Roughness Data

Table 8 suggests a quadratic regression model to be adequate, and an accurate fit for the surface roughness data. In comparison with other listed models, it records a standard deviation of 0.61, PRESS of 15.31, R-square value of 0.9749, adjusted R-square value of 0.9615, and predicted R-square value of 0.9398. Table 9 shows the model to be significant for accurate prediction of the surface roughness (R_a) within the selected design limits of A, B and C. It also shows the model terms, B, C, AB, AC, A^2 and C^2 to be significant. The dominance of influence of A, B and C on R_a begins with B, followed by C, and then, A, for the linear terms. It starts with

$$R_a = 4.79 + 0.23A + 1.32B - 0.63C + 0.85AB + 3.28AC + 0.04BC + 2.94A^2 + 0.5B^2 + 1.72C^2 \quad (4)$$

$$R_a = 67.90158 - 23.62775A - 36.62862B - 0.28959C + 11.30778AB + 0.046801AC + 0.0075873BC + 2.93689A^2 + 89.66914B^2 + 0.0003517C^2 \quad (5)$$

Table 8. Model summary statistics.

Source	Standard Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	3.06	0.1543	0.0440	-0.2195	309.94	
2FI	1.97	0.6951	0.6037	0.4362	143.29	
Quadratic	0.61	0.9749	0.9615	0.9398	15.31	Suggested
Cubic	0.73	0.9790	0.9454	0.8300	43.21	Aliased

Table 9. ANOVA for response surface quadratic model for surface roughness.

Source	Sum of Squares	Degree of Freedom	Mean Square	F Value	p-value Prob> F	
Model	247.76	9	27.53	73.24	< 0.0001	significant
A-Tool Nose Radius	0.99	1	0.99	2.64	0.1228	
B-Feed Rate	31.13	1	31.13	82.82	< 0.0001	
C-Cutting Speed	7.11	1	7.11	18.91	0.0004	
AB	8.63	1	8.63	22.96	0.0002	
AC	128.79	1	128.79	342.65	< 0.0001	
BC	0.019	1	0.019	0.051	0.8246	
A^2	51.75	1	51.75	137.68	< 0.0001	
B^2	1.53	1	1.53	4.06	0.0600	
C^2	17.82	1	17.82	47.40	< 0.0001	
Residual	6.39	17	0.38			
Cor Total	254.15	26				

Table 10. Quadratic model statistics.

Standard Deviation	0.61	R-Squared	0.9749
Mean	8.24	Adjusted R-Squared	0.9615
C.V. %	7.44	Predicted R-Squared	0.9398
PRESS	15.31	Adequacy Precision	29.644

Figure 9a shows how well the predicted R_a data fits the actual data. Figure 9b shows R_a to have nonlinear relationship with A, B and C. It also shows the influence of A and C on R_a to be significant at low and high levels of their

values, whereas that of B on R_a is shown to be significant only at high level of its value. It should be noted that R_a decreased to the reference point as A and C increased, and then, increased, whereas it increased continuously as B increased. These behaviors have the implication of R_a being minimized when A, and C are set at the intermediate level of their values, whereas C is set at the extreme low level of its value. They can also be seen in the contour and response surface plots given in Figs 10 to 12, and attributed to the observed interactions of the process variables, A, B and C.

Figure 9. (a) Predicted vs actual, and perturbation plots for R_a .

Figure 11. Contour and response surface plots of R_a against A and C with B set at 0.225 mm/rev.

Figure 12. Contour and response surface plots of R_a against B and C with A set at 1 mm.

3.3. Parameter Optimization

The surface roughness (R_a), and the machining induced vibration (V_i) are both undesirable and uncontrollable quality characteristics of a turning process. As such, they are to be minimized to improve on product quality subject to constraints determined by the design limits of the process variables. Figure 13, therefore, gives the optimum setting of

Figure 13. Results of parameter optimum.

3.4. Surface Roughness Versus Machining Induced Vibration

The machining induced vibration (V_i) should have influence on surface roughness (R_a) as excess of it impacts negatively on the cutting zone in a turning operations. However, a nonlinear relationship is observed in the plot of R_a versus V_i (Fig. 14). The R-square value of 0.1282 indicates there is no significant correlation between these process characteristics within the experimental design limits. However, there may be correlation outside these limits.

Figure 14. A plot of R_a against V_i .

4. Conclusion

Modeling, prediction and optimization of the machining induced vibration of the cutting tool, and the surface

roughness of the work-piece as functions of the tool nose radius, feed rate and cutting speed has been undertaken. Response surface methodology, based on the central composite design of experiment was used in a turning experiment in which 41Cr4 alloy special steel was turned on a conventional lathe with standard cutting tool, and the response parameters measured. Analyses and optimization of the generated response characteristics data was performed using the Design Expert version 9.0.6.2 software. The following conclusion was reached.

- The selected process and quality characteristics can accurately be predicted within limits of the tool nose radius, feed rate, and the cutting speed using the developed regression models.
- The machining induced vibration data fits well with a quadratic regression model. The relationship of the machining induced vibration with each of the tool nose radius, feed rate and cutting speed is nonlinear. In terms of significance, the effect of the tool nose radius and cutting speed on the machining induced vibration is more at low and high levels of their values, when compared to that of feed rate. The machining induced vibration would be minimized when the tool nose radius is set at higher level of its values; the feed rate is set at either lower or higher level of its values; and the cutting speed is set at the reference point.
- Again, the surface roughness data for the work-piece fits well with a quadratic regression model. Its relationship with each of the tool nose radius, feed rate

and cutting speed is nonlinear. The influence of tool nose radius and cutting speed on surface roughness is significant at low and high levels of their values, whereas that of feed rate on surface roughness is significant only at high level of its value. The surface roughness is minimized when the tool nose radius and cutting speed are set at their intermediate values, and the feed rate set at its extreme low value.

- d. Within the selected design space, the optimum setting of the tool nose radius at 1.72301 mm, feed rate at 0.15 mm/rev, and cutting speed at 311.075 rev/min, would minimize V_f to a value of 0.08 mm/min² and R_a to a value of 4.74 μ m with desirability of 0.948.
- e. There is a nonlinear relationship, and no significant correlation between the surface roughness and the machining induced vibration. This is suggested by the R-square value of 0.1982. However, there may be correlation outside the limits of the selected process variable.

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