The International Journal Of Engineering And Science (IJES)
|| Volume || 5 || Issue || 7 || Pages || PP -34-44 || 2016 ||
ISSN (e): 2319 – 1813 ISSN (p): 2319 – 1805

Modeling and Optimization of Surface roughness and Machining Induced Vibration in 41cr4 Alloy Structural Steel Turning Operation Using Design of Experiment

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ABSTRACT

This paper presents the machining induced vibration and surface roughness modeled, predicted and optimized as functions of the cutting tool overhang, feed rate and cutting speed during hard and high speed turning of 41Cr4 alloy structural steel on an engine lathe machine with a carbide tool. The response surface methodology, based on central composite design of experiment was adopted, and analysis facilitated by using the Design Expert 9 software to generate and validate the models, predict the effect of the process variables on the response variables as well as obtain the optimum setting of the process variables that would minimize the response variables. Quadratic regression models were suggested as best fit for the measured machining induced vibration and surface roughness data. All the model terms of the machining induced vibration are significant with exception of the square term of the tool overhang. Whereas, all those of the surface roughness are significant with exception of the linear term of the tool overhang. The optimum setting of the cutting tool overhang at 57.8784 mm, feed rate at 0.15 mm/rev and the cutting speed at 328.507 rev/min minimized the machining induced vibration to a value of 0.18 mm/s^2, and the surface roughness to a value of 4.399 µmm with desirability of 0.822. Within the selected experimental design limits, the obtained response surface models can be used to accurately predict and optimize the machining induced vibration and surface roughness as functions of the tool overhang, feed rate and cutting speed during hard turning of 41Cr4 alloy structural steel.

Keyword*: Cutting Speed, Depth of Cut, cutting Tool Overhang, Machining Induced Vibration, Surface roughness, Central Composite Design of Experiment, Response Surface methodology*

Date of Submission: 17 May 2016 Date of Accepted: 15 July 2016

I. INTRODUCTION

High-speed machining has attracted the attention of stakeholders in manufacturing industry. This has been attributed to its enhanced production rate as well as desired product quality. However, surface roughness of work-piece and tool vibration isadversely affected by higher and arbitrarily selected values of cutting variables. Besides,the component precision and tool life are hampered by tool vibration (Bhogal et al., 2015). The application of empirical equation has been suggested by several researchers (Suresh et al., 2002; Kumar and Thirumurugan, 2012; Routara et al., 2009; Rahim et al., 2009; Ding et al., 2010). Use of modern techniques has also be suggested (Aggawal and Singh, 2005; Kumar and Uppai, 2013). Further survey of literatures shows that machining parameters like feed rate, cutting speed, and depth of cut influence both work-piece surface roughness and tool vibration. The researches were mainly targeted on investigating the cutting force, tool wear, power consumption, and surface roughness of the machining process.These works, which also support this work to a large extent, include the works of Ozcakar and Kasapoglu, 2009;, Abhang and Hameedullah, 2010;Sahoo, 2011;Abhang and Hameedullah, 2011;Sastry and Devi, 2011; Srinivasan et al, 2012;Ramudu and Sastry, 2012;Aruna and Dhanalaksmi, 2012;Chomsamutr and Jongprasithporn, 2012;Abhang and Hameedullah, 2012; Manu et al, 2013;Makadia and Nanavati, 2013; Kannan et al, 2013;Phate and Tatwawadi,2013;Bhuiyan and Ahmed, 2013; Manohar et al, 2013;Thiyagu et al, 2014; Saini and Parkash, 2014;Saini et al, 2014;Soni et al, 2014;Shunmugesh et al, 2014; Kumar, 2014;Sastry et al, 2015;Revankar et al, 2015; Mahajan et al, 2015;Shihab et al, 2015; Gupta and Kohli, 2015; Khan et al, 2015;Devkumar et al, 2015; Devi et al, 2015;Rajpoot et al, 2012;Khidhir et al, 2013; Agrawal et al, 2013;Ranganath et al, 2014; and Chandra and Prasad, 2014. Few other studies have been reported to have been conducted to minimize the tool vibration during turning operation. These include the works of Kassab and Khoshnaw, 2007; Han et al, 2009;Cahuc et al, 2010;Delijaicov et al, 2010;,Rogov and siamak, 2013 and 2014. Whereas no study is published on the application of design of experiment to investigate the surface roughness and machining induced vibration in 41Cr4 alloy structural steel during turning operation except in a series turning experiment of which this is an aspect. Owing to great application of the structural steel, the study was aimed to find out the best combination of machining parameters in high-speed turning of 41Cr4 alloy structural steelto achieve minimum machining induced vibration and surface roughness. For this purpose, mathematical models have been developed for the machining induced vibrations (V_i) and surface roughness (R_a) as functions of the cutting tool overhang (A), feed rate (B) and cutting speed (C).Using the experimental data,the developed models are tested for adequacy, and finally, the optimum setting of the machining variables that would minimize the response variable are determined.

II. MATERIALS AND METHODS

2.1 Materials and machine

The YUCY 6240B Engine lathe machinewas employed for this research work in conjunction withtype F30 carbide cutting tool. The overall dimensions of the tool insert are 25 mm x 25 mm x 12.5 mm. Its back rake angle is 10^o, side rake angle is 12^o, side relief angle is 5^o and side cutting edge angle is 15^o. The work piece used was 41Cr4 alloy special steel as revealed by the chemical analysis and mechanical test of the work-piece material.The chemical composition and mechanical properties of 41Cr4 alloy special steel (Plate 1)was performed at Standards Organization of Nigeria, Emene, Enugu. The results are presented in Tables 1 and 2, respectively.

Plate 1: 41Cr4 Alloy Steel Bars

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

2.2 Experimental Procedure

The turning operation is conducted on a YUCY 6240B engine lathe at the Nigerian Defence Academy, Kaduna with a set up given in Plate 2. Themachining induced vibration (V_i),measured acceleration amplitude,was determined using avibration transducer suchas given in Plate 3, while that of surface roughness (R_a) was measured with a surface roughness tester such as given in Plate 4. The experimental was replicated, and the average results evaluated.

Plate 2: Setup for the Turning Experiment

Plate 3: Vibration Meter with Transducer, 908 BE

Plate 4: Surface Roughness Tester, ISR-16

2.3 *Experimental design*

A response surface methodology, based on central composite experimental design was selected. Also selected are three independent variables as well astwo response variables. The influence of the independent variables, A, (work-piece overhang, mm), B (feed rate, mm/rev) and C (depth of cut, mm) on the response variables, R_a (surface roughness, µmm) and V_i (machining induced vibration, mm/s^2) is investigated in the turning experiment. The selected levels of the independent variables are given in Table 3. A total of 27 runs of the experiment were conducted separately for determining the surface roughness (R_a) and machining induced vibration (V_i).

Table 3: Levels of the Independent Variables

Variables	**Levels**	
	Lower	**Upper**
Tool Overhang (mm) (A)	50	60
Feed rate(mm/rev) (B)	0.15	0.30
Cutting speed (rev/min)(C)	260	400

2.4 *Statistical analysis*

The Design Expert 9.0.6.2 software was employed for analysis of the generated data. The surface roughness (R_a)and machining induced vibration (V_i) were taken as the responses in the turning experiment defined as functions of the independent variables taken as cutting tool overhang (A), feed rate (B) and Cutting speed (C). The general form of the required regression modelsresulting as best fits for the experimental data is polynomial equation given as:

$$Y_{(predict)} = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_i x_i^2 + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} x_i x_j + e \qquad (1)$$

Note that Y denotes the response variables; β_0, β_i, β_{ii} and β_{ij} are coefficients of the constant, linear, quadratic and cross product terms of the regression equation, respectively; x_i and x_j denotes the independent variables, k is the number of factors studied and optimized in the experiment.

III. RESULT AND DISCUSSION

In the current study, optimization of hard turning operation on 41Cr4 alloy structural steel was carried out using the response surface methodology. An experimental plan with threefactorsof three levels each was chosen(Table 3). Table 4 depicts the design layout for the turning experiment in terms of actual values the independent variables, and observed responses. This includes all of the 27 runs of the experiment conducted. Analysis and optimization based on this result was achieved using Design expert 9.0.6.2 software and the outcome documented as follows:.

3.1 RegressionModels

The quadratic regression models were suggested for both the machining induced vibration (V_i) and surface roughness (R_a) data. For the machining induced vibration (V_i)data,V_i is given as a function of the coded and actual factors, A, B and C in the form of Eqns. (2) and (3), respectively.

$$V_i = 0.18 + 0.016\,A - 0.017\,B + 0.021\,C + 0.024\,AB - 0.029\,AC - 0.028\,BC - 0.005\,A^2 - 0.015\,B^2 + 0.011\,C^2 \quad (2)$$

$$V_i = 0.58467 + 0.038222\,A - 0.79312\,B - 0.00895\,C + 0..064444\,AB - 0.000083\,AC - 0.005397\,BC - 0.0002\,A^2 - 2.66667\,B^2 + 0.0000228\,C^2 \quad (3)$$

Whereas, for the surface roughness (R_a) data, R_a is given as a function of the coded and actual factors of A, B and C in the form of Eqns. (4) and (5), respectively.

$$R_a = 10.33 + 0.002389\,A + 1.8\,B - 1.87\,C + 0.61\,AB + 1.41\,AC + 0.72\,BC + 1.36\,A^2 - 4.27\,B^2 + 2.77\,C^2 \quad (4)$$

$$R_a = 304.19381 - 7.65441\,A + 231.14386\,B - 0.65258\,C + 1.61667\,AB + 0.00402548\,AC + 0.13762\,BC + 0.054207\,A^2 - 758.84444\,B^2 + 0.000565884\,C^2 \quad (5)$$

Table 4: Response for the turning operation of 41 Cr4 alloy steel bars

Standard	**Run**	**A Tool Overhang [mm]**	**B Feed Rate [mm per rev]**	**C Cutting Speed [rev per min]**	V_i **Acceleration Amplitude [mm per min square]**	R_a **Surface Roughness [micro mm]**
1	26	50	0.15	260	0.21	12.857
2	22	55	0.15	260	0.24	9.000
3	8	60	0.15	260	0.25	8.780
4	5	50	0.225	260	0.23	18.010
5	7	55	0.225	260	0.28	15.860
6	2	60	0.225	260	0.32	15.350
7	23	50	0.3	260	0.20	14.193
8	25	55	0.3	260	0.28	11.125
9	17	60	0.3	260	0.32	12.080
10	3	50	0.15	330	0.20	6.790
11	12	55	0.15	330	0.19	4.403
12	16	60	0.15	330	0.19	5.430
13	13	50	0.225	330	0.15	11.000
14	10	55	0.225	330	0.16	9.830
15	18	60	0.225	330	0.21	11.180
16	19	50	0.3	330	0.09	8.319
17	14	55	0.3	330	0.14	8.170
18	1	60	0.3	330	0.18	10.335
19	4	50	0.15	400	0.37	4.839
20	15	55	0.15	400	0.35	4.088
21	24	60	0.15	400	0.29	6.905
22	6	50	0.225	400	0.33	11.570
23	27	55	0.225	400	0.31	11.345

24	21	60	0.225	400	0.28	13.560
25	20	50	0.3	400	0.24	8.560
26	9	55	0.3	400	0.26	10.142
27	11	60	0.3	400	0.27	12.561

3.2 Evaluation of the models

Presented in Tables5 is the precision index values of the different models derived from the model statistics, and analysis of variance (ANOVA) employed to validate the stability of the models for the various responses.As demonstrated in Table 5, there are indications that the observed quadratic regression modelsare significant since p values are less than 0.0001, and the adjusted and predicted of R^2 are more than 90%. The regression statistics of fits (R^2),that is, goodness of fit for V_i (0.9735),and that of R_a (0.9842), are very close to unity. There are also indications that over 97.35% and 98.42% of the data are adequately captured for V_i and R_a, respectively.Besides, the predicted R-square of 0.9317 for V_i and 0.9637 for R_a are in reasonable agreement with the adjusted R-square of 0.9595 for V_i and 0.9758 for R_a, since the difference of 0.0278 for V_i and 0.0121 for R_a are less than 0.2. The adequacy precision of 32.219 for V_i and 40.123 for R_a, greater than 4, are desirable signal to noise ratios. These indicate that there are adequate signals, and that these models can be used to navigate the design space.The predicted values indicated fits the data appropriately.

Table 5: Precision Index Values of the Different Models

Model	V_i	R_a
Mean	0.24	10.23
Standard Deviation	0.014	0.55
C. V. (%)	5.74	5.39
PRESS	0.008471	11.89
Model degree	Quadratic	Quadratic
R^2	0.9735	0.9842
Adjusted R^2	0.9595	0.9758
Predicted R^2	0.9317	0.9637
Adequacy Precision	32.219	40.123

Table 6: ANOVA for Response Surface Quadratic Model for Acceleration Amplitude (V_i)

Source	**Sum of Squares**	**Degree of Freedom**	**Mean Square**	**F Value**	**p-value Prob > F**	
Model	0.12	9	0.013	69.49	< 0.0001	significant
A-Tool Overhang	4.672E-003	1	4.672E-003	24.19	0.0001	
B-Feed Rate	5.339E-003	1	5.339E-003	27.64	< 0.0001	
C-Cutting Speed	7.606E-003	1	7.606E-003	39.38	< 0.0001	
AB	7.008E-003	1	7.008E-003	36.29	< 0.0001	
AC	0.010	1	0.010	52.86	< 0.0001	
BC	9.633E-003	1	9.633E-003	49.88	< 0.0001	
A^2	1.500E-004	1	1.500E-004	0.78	0.3905	
B^2	1.350E-003	1	1.350E-003	6.99	0.0171	
C^2	0.075	1	0.075	387.38	< 0.0001	
Residual	3.283E-003	17	1.931E-004			
Cor Total	0.12	26				

Analysis of variance of Table 6 shows that all the model terms have significant influence on V_i with exception of the square of the cutting tool overhang (A). For the linear terms, the C has dominant influence on V_i followed by B and then A. For the square terms, C^2 has much more dominant influence on V_i followed by B^2, and then, A^2. Whereas, for the cross product terms, AC has dominant influence on V_i followed by BC, and then, AB. Analysis of variance of Table 7 reveals that all the model terms have significant influence on R_a with exception of the linear form of cutting tool overhang (A). For the linear terms, C has a dominant influence on R_a, followed by B, and then, A. For the square terms, B^2 has a dominant influence on R_a, followed by C^2, and then, A^2. For the cross product terms, AC has dominant influence on R_a, followed by BC, and Then, AB.

Table 7: ANOVA for Response Surface Quadratic Model for Surface Roughness (R_a)

Source	Sum of Squares	Degree of Freedom	Mean Square	F Value	p-value Prob> F	
Model	322.30	9	35.81	117.61	< 0.0001	significant
A-Tool Overhang	1.027E-004	1	1.027E-004	3.374E-004	0.9856	
B-Feed Rate	58.29	1	58.29	191.45	< 0.0001	
C-Cutting Speed	63.04	1	63.04	207.03	< 0.0001	
AB	4.41	1	4.41	14.49	0.0014	
AC	23.82	1	23.82	78.23	< 0.0001	
BC	6.26	1	6.26	20.57	0.0003	
A^2	11.02	1	11.02	36.19	< 0.0001	
B^2	109.32	1	109.32	359.04	< 0.0001	
C^2	46.13	1	46.13	151.51	< 0.0001	
Residual	5.18	17	0.30			
Cor Total	327.48	26				

3.3 Machining Induced Vibration Model

The plot of the predicted versus actual V_i**,** given in Fig. 1, depicts that the predicted datais quite close to the experimental data, thereby validating the reliability of the model developed for the correlation between the turning variables, A, B, and C,and the machining induced vibration, V_i .The plot of perturbation,also given in Fig. 1,shows the effect of A, B and Con V_i . It shows that V_i increased with increase in A, but decreased with increase in B. It also shows that V_i decreased with increase in C,and later, increased. The contour and response surface plots of Fig. 2 show the impacts of A and B onV_i. They show that increasing A would lead to increaseinV_i. Whereas, as B increases,V_i decreases. The contour and surface plots of Fig. 3 show the interaction between A and ConV_i. It can be seen from the plots that V_i steadily increased as A increases, but decreased as C increases, and later increased. Similar trend was observed in Fig. 4 about the interaction of B and C onV_i .

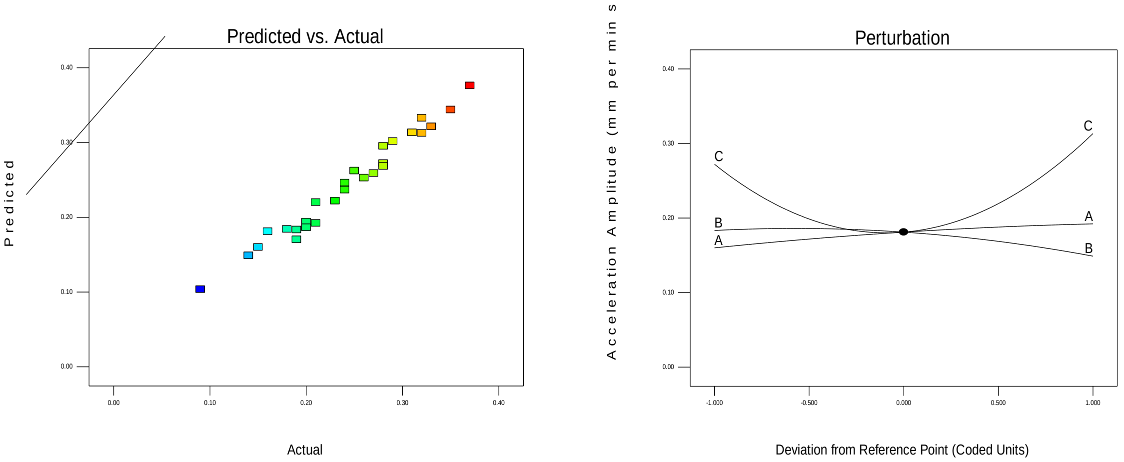

Figure1. Predicted vs Actual, and Perturbation plots for V_i

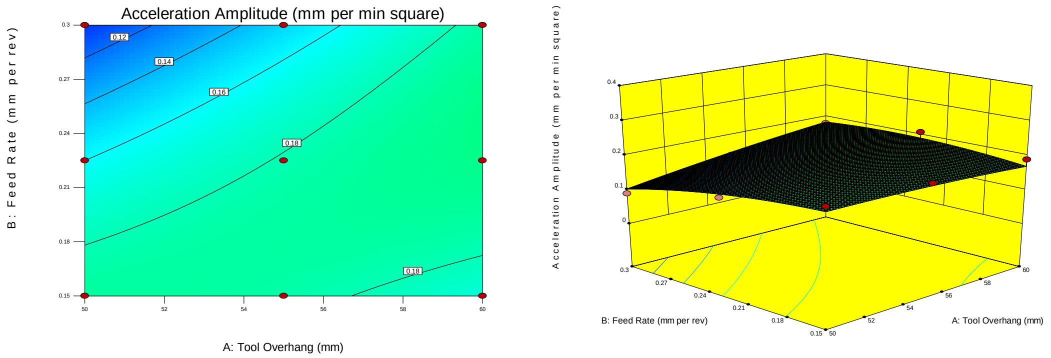

Figure 2 Contour and Response Surface plots of V_i against A and B with C set at 330 rev per min

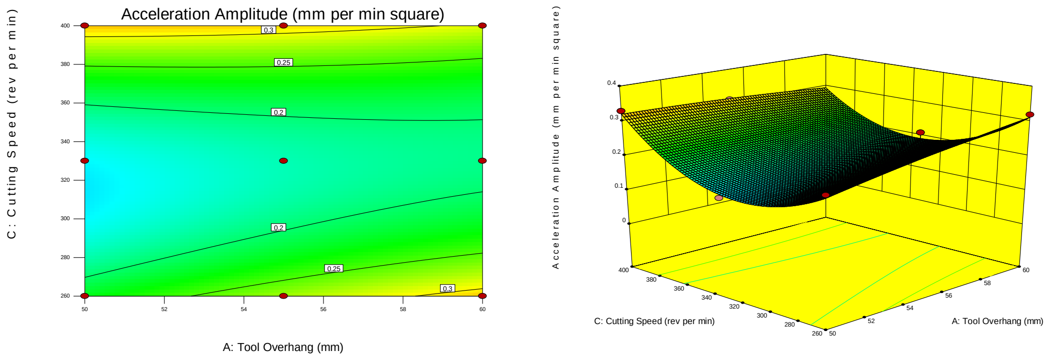

Figure 3 Contour and Response Surface Plots of V_i against A and C with B set at 0.225 mm/rev

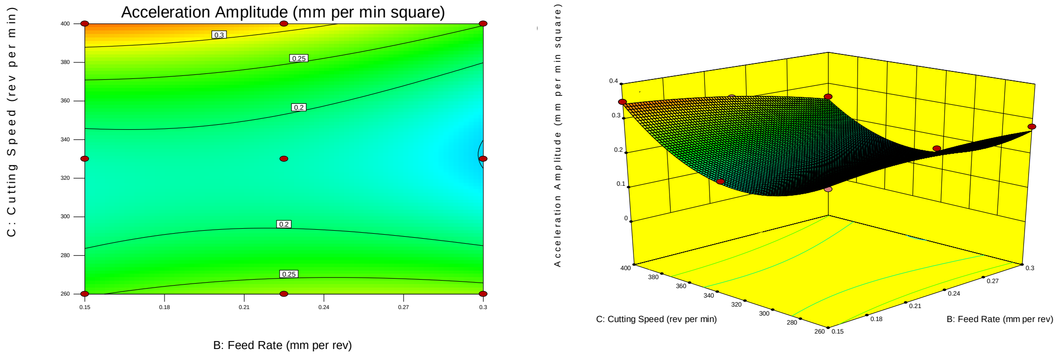

Figure 4 Contour and Response Surface Plots of V_i against B and C with A set at 55 mm

3.4 Surface roughness model

Figure 5 depicts that the predictedand actual surface roughness datafits well with each other as the correlation is very close, thereby, validating surface roughness model. It shows, in a perturbation plot the effect A, B, and C have onthe surface roughness (R_a). It shows that R_a decreases with increase in A and C, and later slightly increased. Besides, R_a increased with increase in B, and later, decreased.Figure. 6 shows the interactive effect of A and B over R_a in contour and response surface plots. The plots reveal that R_a increased asA and B increased, but decreased later as B increased. The interaction of A and C on R_a is depicted in Fig. 7. As shown in the plots, R_a decreased as Aincreases. On the same plots, increasing in C lead to increase in R_a.The effect of B and C on R_a is depicted in Fig. 8. The surface roughness (R_a) was at the peak at feed rate of 0.225 mm/rev and cutting speed of 330 rev/min.

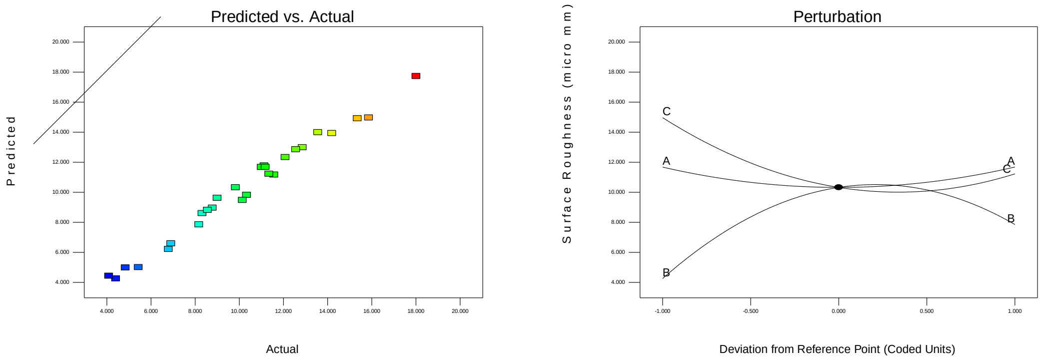

Figure 5 Predicted vs Actual, and Perturbation Plotsfor R_a

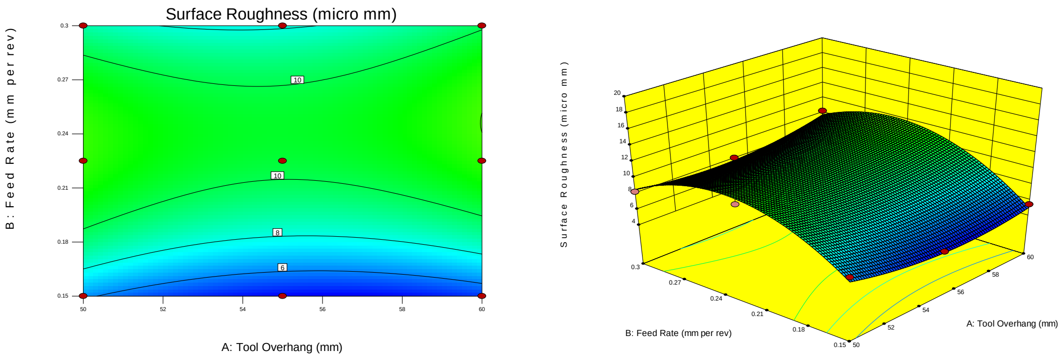

Figure 6 Contour and Response Surface Plots of R_a against A and B with C set at 330 rev per min

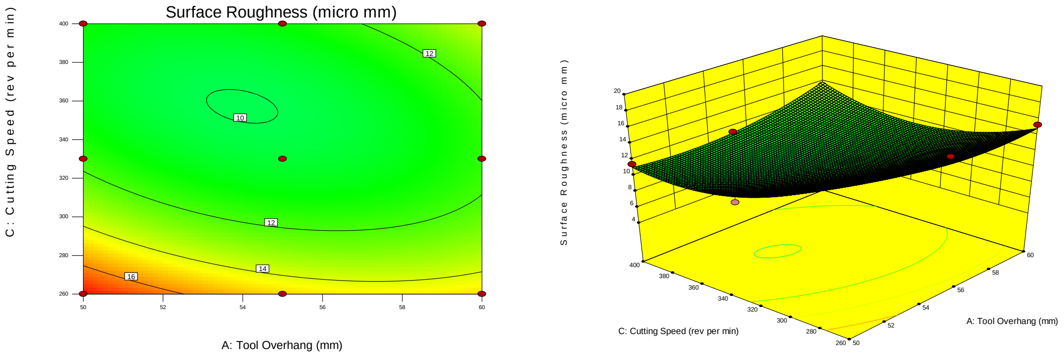

Figure 7 Contour and Response Surface Plots of R_a against A and C with B set at 0.225 mm/rev

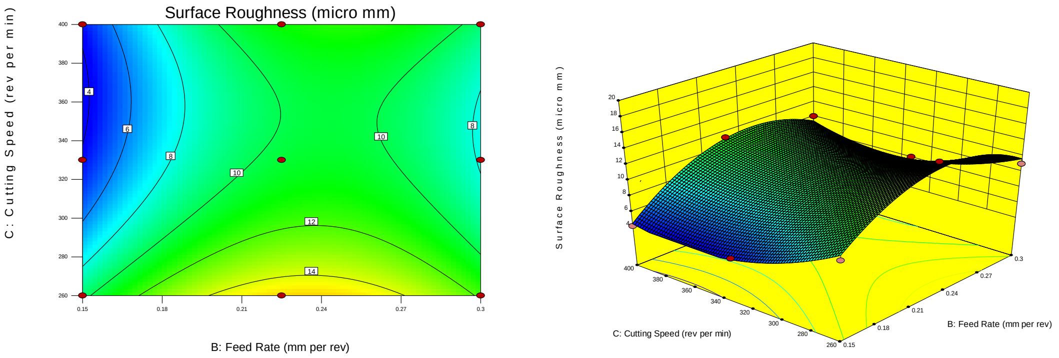

Figure 8 Contour and Response Surface Plots of R_a against B and C with A set at 55 mm

3.5 *Parameter optimization*

The optimal turning conditions were calculated by solving the regression model (eqn. 1) according to the limit criterion of minimizing acceleration amplitude (V_i) and surface roughness (R_a). The outcomeis as depicted in Fig.9. Thus, the tool overhang of 57.87 mm; the feed rate of 0.15 mm/rev; and the cutting speed of 328.507 rev/mm, which resulted into minimalacceleration amplitude of 0.18 mm/s^2 and surface roughness of 4.399 µmm.

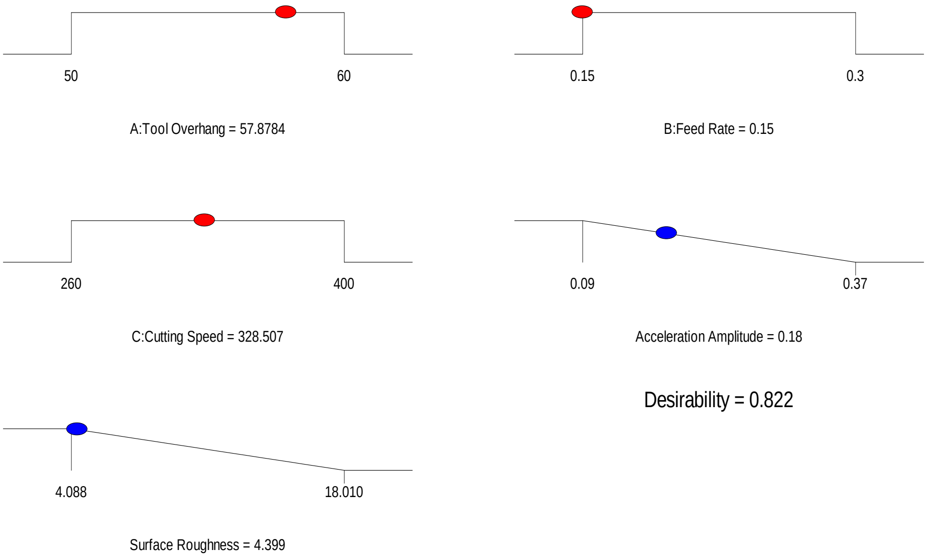

Figure 8: The optimal conditions with minimal surface roughness and acceleration amplitude

3.6 *Surface Roughness versusMachining Induced Vibration*

If excessive, the machining induced vibration (V_i) should have influence on surface roughness (R_a) as it impacts negatively on the cutting zone in a turning operations. However, the plot of R_a versus V_i given in Fig 14, shows a nonlinear relationship, but no significant correlationbetween these process characteristics within the experimental design limits. This can be seen from the R-square value of the trend line of 0.1122, but there may be correlation outside these limits.

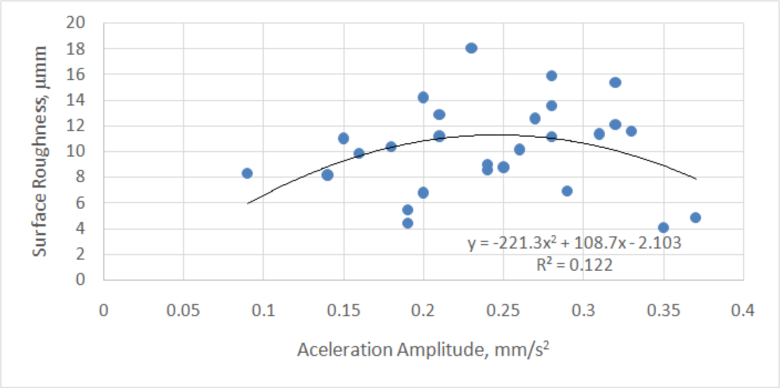

Figure 14: A plot of R_a against V_i

IV. CONCLUSION

By using design of experiment, like the response surface methodology, an empirical relationship was developed to predict and optimize machining induced vibration and surface roughness defined as functions of the cutting tool overhang, feed rate and cutting speed during hard turning of 41Cr4 alloy structural steel. The results revealed the developed mathematical modelsto be accurate, effective and reliable, and therefore, can be employed in the prediction and optimization of the induced machining vibration and surface roughness, but within limits of the selected machining variables. It also indicated that design of experiment is an appropriate tool for this purpose.

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