Optimizing Machining Parameters during Turning Process

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Abstract: This work presents an experimental investigation of the influence of the three most important machining parameters of depth of cut, feed rate and spindle speed on surface roughness during turning of mild steel. In this study, the design of experiment which is a powerful tool for experimental design is used to optimize the machining parameters for effective machining of the workpiece. Box Behnken experimental design method as well as analysis of variance (ANOVA) is used to analyze the influence of machining parameters on surface roughness height Ra. The individual parameters effect as well as effect of interactions between the machining parameters on the surface roughness height Ra is analyzed using various graphical representations. Using multiple linear regressions, mathematical models correlating the influence of machining parameters on the surface roughness Ra during the machining process were developed. Confirmation results were used to confirm that mathematical models are good enough to effectively represent machining criteria of surface roughness Ra during the study.

Keywords: Box Behnken, machining parameters, mathematical model, optimization, surface roughness.

1. Introduction

Carbon steels are by far the most frequently used industrial steels because of their high production volume, good formability as well as weldability properties. They are used increasingly in most industrial/commercial applications such as in automobile- (body panels; crankshafts; gears; axles) construction industries- (structural steels; hammer; seamless tubes) industrial and machine tools industries- (chains; stampings; pipes; lead screws; rivets; nails; spindles; wrenches; band-saws; shafts and machine parts) [1]. Nevertheless, because of carbon steels wider area of applications coupled with its low cost and availability, machining characteristics of its surface roughness need to be optimized to further increase its area of application as well as achieving high quality products [1-3].

Surface roughness plays an important role in evaluating quality of machined products. The quality of surface is of utmost important for the correct functioning of machine parts which directly affect the attributes of product such as friction, fatigue, wear resistance, coating, reflection and lubricant [4-5]. There are many factors that affect surface roughness of any machined parts, these factors among others includes: machining parameters, tool geometry, workpiece material, nature of chip produced, machine rigidity and cutting fluids used [6- 7].

In other to achieve the specified roughness, a trade-off between the factors that affect the surface roughness is always made. This paper focuses on the machining factors of feed rate, spindle speed and cutting speed.

A number of authors have researched into surface roughness with respect to machining parameters. These literatures are referenced in [8-13]. In this study, the design and the analysis have been carried using Design-Expert version 8.0.4. The investigations carried out included the effect and optimization of the cutting parameters.

2. Tool and Workpiece Materials

The workpiece used was medium carbon steel (AISI 1045) with molybdenum High Speed Steel (HSS) turning tool.
AISI designation of the tool is Grade M-7, (1%C, 3.8%Cr, 9.5%Mo, 1.6%W and 2%V). The tool signature is: rake angle (back-10^0, side-12^0), cutting edge angle - 15^0, relief angle-5^0; and nose radius of 0.5mm.

2.1 Machining Parameters and Experimental Design

The three machining parameters considered for this study were feed rate (mm/min), cutting speed (m/min) and the spindle speed (rpm). The parameters were set at three levels each. The summary of the parameters are shown in Table 1.

Table 1 Different machining parameters used in the experiment and their levels

Parameter	Coding	Levels		
		-1	0	+1
Feed rate (mm/min)	X_1	0.5	0.8	1.0
Cutting speed (m/min)	X_2	47.12	70.69	94.25
Spindle speed (rpm)	X_3	1000	1500	2000

This study evokes a Box-Behnken design which requires 3-levels of each factor coded as -1, 0 and 1. The experimental design for this study combines 2-level

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designs with incomplete block. This method creates designs with a fraction of the experiments required for 3-level factorials. The total numbers of experimental runs were 15. This was generated from a center point with three replicates coupled with all possible pairs of 2^2 designs for the three factors which is $\{3(2^2)\}$.

2.2 Experimentations

The experiments were carried out on Meuser lathe machine, model KM3-46083. The workpiece dimension is 25mm diameter and 170mm length for length-diameter ratio (L/D) of less than 10 in line with ISO 3685 standards. The cutting conditions were randomized according to Box-Behnken design. Qualitest micro-trio-gloss (model No. 4430Nr-05643) was used to measured the Ra

Table 2 Design matrix and the response

Run	X_1	X_2	X_3	Surface roughness (μm)
1	-1	-1	0	0.18
2	0	0	0	0.25
3	-1	1	0	0.2
4	0	1	1	0.14
5	0	1	-1	0.211
6	0	0	0	0.27
7	1	0	1	0.3
8	-1	0	-1	0.18
9	0	0	0	0.27
10	1	1	0	0.315
11	-1	0	1	0.16
12	0	-1	1	0.15
13	0	-1	-1	0.14
14	1	-1	0	0.29
15	1	0	-1	0.33

3. Results

Employing the parameters in Table 1, the levels of the parameters for each of the experimental runs in the design matrix and the observed response are given in Table 2.

The general equation for the proposed second order regression model to predict the response y can be written as:

$$y = a_0 + a_1 x_1 + a_2 x_2 + a_3 x_3 + a_{11} x_1^2 + a_{22} x_2^2 + a_{33} x_3^2 + a_{12} x_1 x_2 + a_{13} x_1 x_3 + a_{23} x_2 x_3 \qquad (1)$$

All the coefficients are to be estimated using experimental data. Based on the result presented in Table 2, the derived model equation is shown in Eq. (2).

Surface roughness R_a

$= -0.74372 \ -0.5245*X_1 \ +0.015759 * X_2 +0.000734647*X_3 -0.00000171683* X_2 * X_3 +0.52133 * (X_1)^2 -0.0000892502 * (X_2)^2$
$-0.000000213667 * (X_3)^2 \qquad (2)$

From Eq. 2, the most significant parameter is X_1 followed by X_2. X_3 has least effect on Ra. The missing terms in the equation are: X_1X_2 and X_1X_3. These terms are not significant for predicting Ra hence they were removed in other to improve the model.

3.1 Adequacy Check for the Developed Model

The adequacy of the model was checked by analysis of variance (ANOVA). The ANOVA, table 3 for Ra shows that the p-value for model is less than 0.05, which indicates that the model is significant. The main effects of each linear factor as well as their quadratic effect are significant model terms. The model has significant interaction of cutting speed and spindle speed $(x_2 x_3)$. Table 3 shows that the p-value for $(x_2 x_3)$ is less than 0.05 for Ra, this means that the effect of cutting speed on Ra depends on the spindle speed. The "Lack of Fit F-value" of 0.91 implies its insignificant relative to the pure error. Non-significant lack-of-fit is required for any model to be fitted.

Table 3 ANOVA table (partial sum of squares) for response surface reduced quadratic model

Source	DF	SS	MS	F	P
Model	7	0.062	0.008849	70.94	0.0001*
X_1	1	0.033	0.033	265.78	0.0001*
X_2	1	0.001405	0.001405	11.26	0.0122*
X_3	1	0.00154	0.00154	12.35	0.0098*
$X_2 X_3$	1	0.00164	0.00164	13.15	0.0084*
X_1^2	1	0.00392	0.00392	31.43	0.0008*
X_2^2	1	0.009108	0.009108	73.02	0.0001*
X_3^2	1	0.011	0.011	84.46	0.0001*
Residual Error	7	0.0008732	0.0001247		
Lack-of-Fit	5	0.0006065	0.0001213	0.91	0.5979**
Pure Error	2	0.0002667	0.0001333		
Total	14	0.063			
$R^2=0.986$;		R^2 (Adj) = 0.972			

*Significant; **Not significant; DF– Degree of freedom; SS – Sum of squares; MS – Mean square.

Checking the model adequacy, the experimental and predicted data (Fig. 1) for Ra were plotted. Fig. 1 and ANOVA analyses Table 3 for Ra indicate that the model (Eq. 2) is significant and adequate to represent the relationship between the variables and response, with very small P values (<0.05) and high value of coefficient of determination ($R^2 = 0.986 \approx 0.99$).

Additionally, the developed response surface model for Ra has been checked by using residual analysis. The residual plots for Ra are shown in Figs. 2-4. In normal probability plot, the data are spread approximately in a

straight line, which show a good correlation between experimental and predicted values for the response (Fig. 2). The plot of residual versus predicted values show minimal variation between the observed and fitted values (Fig. 3). Fig. 4 is the plot of the residuals calculated against the order of experimentation. It is asserted that a tendency to have runs of positive and negative residuals indicate the existence of correlation [14]. From the above analysis of residual plots for *Ra*, the model does not reveal inadequacy.
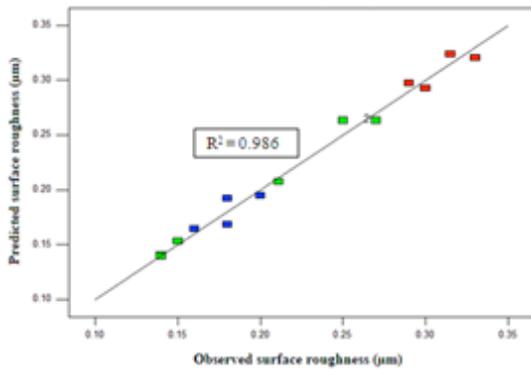
Fig. 1 Plot of experimental and predicted *Ra*.
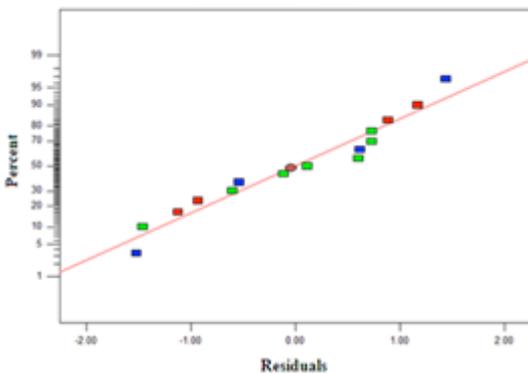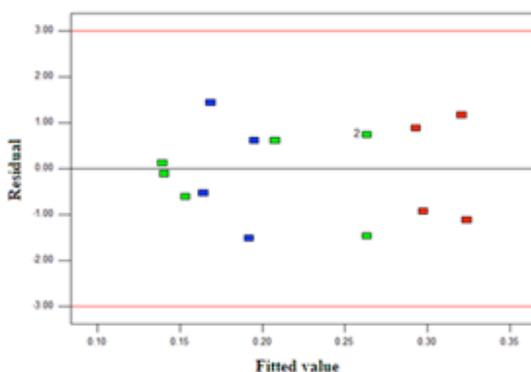

Fig. 2 Normal probability plot of residuals.
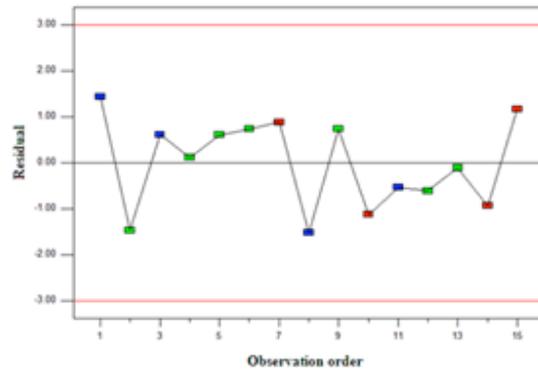

Fig. 3 Plot of residuals and fitted values.

Fig. 4 Plot of residuals vs. order of the data.

3.2 Effect of Machining Parameters on *Ra*

Figs. 5a, b, c and d show the effect of feed rate (X_1), cutting speed (X_2), spindle speed (X_3) as well as the interaction between cutting speed and spindle speed ($X_2 X_3$) on *Ra* respectively. These figures are appropriate for analyzing data in a designed experiment, with respect to important factors, where the factors are at two or more levels [14].

It can be observed from Fig. 5a, that initially at 0.5 mm/min feed rate, no change in *Ra* value is observed. As the feed rate increases from 0.58 mm/min to the maximum value of 1 mm/min, *Ra* increases steadily. The value of *Ra* is worsen as the cutting speed increases from 47.12 m/min up to 73.66 m/min when *Ra* value begin to decrease as cutting speed increases to its maximum value (Fig. 5b), this observation is in line with the work of [15]. In a similar manner (Fig. 5c) spindle speed has similar effect as cutting speed has on *Ra*.

This phenomenon can be attributed to the fact that, during turning at a low feed rate, the heat generated in the tool-workpiece interface is not high enough to affect either the tool, chip formation or the surface roughness. As the feed increases during machining, more heat per time is being produce per unit area of tool/workpiece zone which affects the sub-surface layer of the wokpiece. Furthermore, the heat generated during turning operation usually affects the chip characteristics which in turn translate to the workpiece surface finish.

For the case of cutting speed and spindle speed, it can be deduced from Figs. 5b and 5c that, the higher the values of the two machining parameters, the more heat is generated during turning operation. This in turn will produce a negative effect on the surface roughness. The case of improved *Ra* during further increase of the two parameters (cutting speed and spindle speed), the reason could be due to the fact that heat generated at tool-workpiece interface has reach the equilibrium hence there is no effect of heat recorded on the *Ra* as the cutting speed and spindle speed increases compare to when they are at low values.

The 3-dimensional (3-D) response surface plot is also formed based on the quadratic model to evaluate the change in response surface as shown in Fig. 6. The effects of interaction $X_2 X_3$ on *Ra*, is shown in Fig. 6. It can be

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seen that increase in cutting speed leads to a sharp increase in *Ra*. In addition, the response *Ra* depends more on the spindle speed rather than on feed rate.
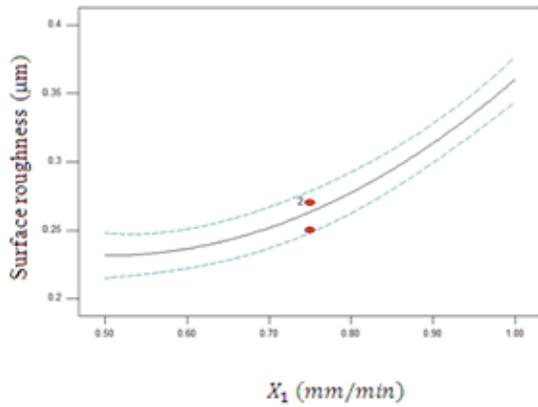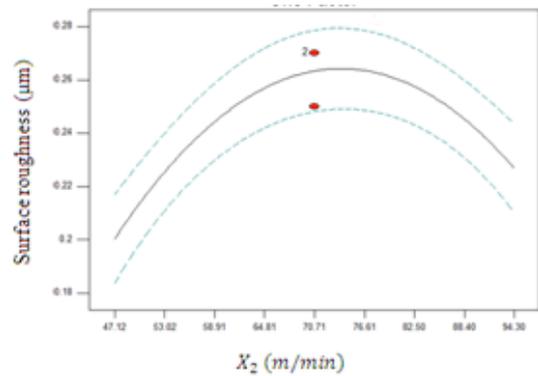

Fig. 5a Effect of feed rate on *Ra*
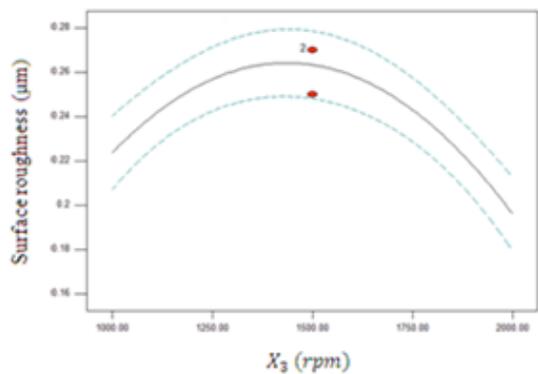

Fig. 5b Effect of cutting speed on *Ra*
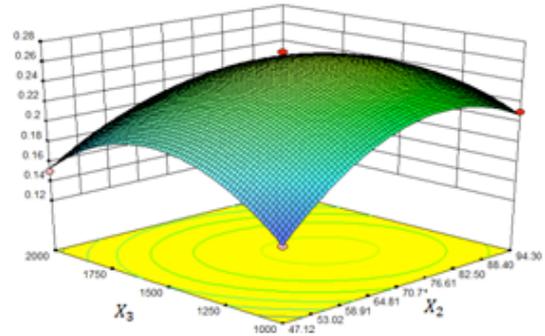

Fig. 5c Effect of spindle speed on *Ra*

Fig. 6 3-D plot of effect of cutting speed and spindle speed on *Ra*

3.3 Optimizing the Surface Roughness

In optimizing the R_a in this work, the interest is to find the best machining parameters that satisfy minimum value for R_a. The set objective is to minimize R_a within the parameters set in Table 3. The optimum solution generated for the experimental condition is $R_a = 0.107579$ µm with machining parameters of X_1 =0.5mm/min, X_2 =94.3m/min and X_3 =2000rpm (Table 4) with 95% desirability. The desirability histogram of the optimized solution for the machining condition is shown in Fig. 7.

Table 4 Optimization solutions generated for R_a

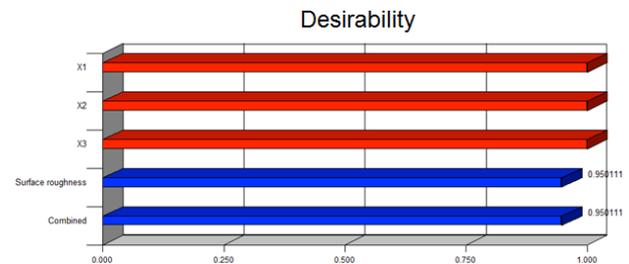| Sol	X_1	X_2	X_3	R_a(µm)	Desirability
1	0.5	94.3	2000	0.107579	0.95
2	0.51	94.3	2000	0.107583	0.95
3	0.5	94.29	2000	0.107622	0.95

Fig. 7 Desirability plot of optimization solution for *Ra*.

Confirmation experiments were carried out by using the model to predict the response at a particular point then compare the predicted response with the actual observation by conducting another experiment at the same point. The predicted values and the actual confirmation experimental values are compared and the residual and percentage error are calculated (Table 5).

Table 5 Analysis of the confirmation experiments for R_a

Run No.	X_1	X_2	X_3	R_a (µm) Actual	Predicted	Residual	% error
1	0.5	94.3	2000	0.121	0.13	0.01	1
2	0.5	47.12	1000	0.057	0.11	0.05	5
3	0.5	47.12	2000	0.092	0.13	0.04	4

4. Conclusion

In this study, optimization of machining parameters during turning process has been carried out. The surface roughness response Ra has been modeled and analyzed through response surface methodology (RSM). A Box-Behnken design was used to carry out the experimental study. Analysis of variance (ANOVA) was used to analyze the effect of the parameters on the response. In summary, the following conclusions can be drawn:

1. The feed rate is found to be the most important parameter effecting Ra, followed by cutting speed while spindle speed has the least effect.
2. Machining with high cutting speed and spindle speed has positive effect on Ra as against feed rate.
3. The predicted value of Ra matches the experimental values reasonably well, with high value of coefficient of determination ($R^2 = 0.99$) for Ra.
4. The variation in percentage error for R_a is between 1 to 5%, which shows that the model developed for R_a is accurate, and can be used for predicting the surface roughness.

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