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Research Article

OPTIMIZATION OF CUTTING PARAMETERS USING THE RESPONSE SURFACE METHOD

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ABSTRACT

Some cutting parameters have to be considered in order to obtain high-quality surfaces in machining. Because poorly selected cutting parameters cause both the cutting tools to wear out quickly and the surface to become rough. Therefore, it is of great importance to use experimental design methods to obtain better quality surfaces with an optimal combination of cutting parameters.
In this study, optimization of cutting parameters such as feed rate, cutting speed and depth of cut, which affects the surface roughness of AISI 1040 steel the commonly used in the industry, is aimed by three-level Box-Behnken design combined with response surface methodology. For this purpose, 15 workpieces with Ø 70 mm and 200 mm length were prepared and machined on a CNC lathe. Then, the surface roughness values of the workpieces were measured. The obtained surface roughness values were analyzed in the Design Expert 10.0.6 program and the cutting parameters affecting the surface roughness were optimized. According to the results obtained from the study, it was determined that the feed rate is the parameter that has the greatest effect on the surface roughness. In addition, optimum surface roughness was determined by a feed rate of 0.2 mm/rev, a cutting speed of 397.58 m/min and a depth of cut 1.5617 mm.
Keywords: Box–Behnken design, response surface methodology, surface roughness.

1. INTRODUCTION

As in the case of machining, it is of great importance that in all production methods, besides the size and geometric tolerances of the product, a satisfactory surface roughness is required. [1, 2]. The performance and mechanical life of machine parts are greatly affected by surface quality [2]. Surfaces processed by the manufacturing methods used in the manufacturing sector are directly or indirectly affected by the processing parameters. Inadequate parameters cause financial losses such as rapid wear and tear of cutting tools as well as loss of workpieces or bad surface quality. [3, 4]. In 1930, the roughness of metal surfaces was assessed by looking at or touching that surface. If there was a high reflection on the surface, the surface was considered smooth. In later years, the evaluation of metal surfaces began to be considered independent of the attention of the person. [5]. In the machine industry, the goodness of the surface quality of the parts allows to raise quality of the production. Especially if the surface of the hardest part of a pair of pieces in contact with each other is very rough, very high wear will occur and this will limit the parts life

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and efficient working ab ility. In traditional and non-traditional manufacturing methods, many factors affect the surface roughness, such as the type of material, cutting tool, cutting speed and feed rate, depth of cut, cooling fluid and construction of the machine. The surface roughness can also be changed by changing one of these factors. However, the effects of the factors that cause change may be different and independent from one another, or they may be related to each other [6]. For this reason, it is seen that the improvement of the surface roughness by increasing the cutting speed as the processing parameters but the increase of the cutting speed increases the tool wear and therefore the tool life is decreased. It is known that the increase in the feed rate increases the roughness of the surface and is the most affected parameter to the surface roughness of the feed rate [7, 8]. Also, depending on the increase in cutting speed, the surface roughness is reduced but the surface roughness is increased due to the increase in depth of cut [9]. Thus, it is stated that the low surface roughness of the finish processing in manufacturing can be obtained by avoiding vibrations due to the reduction of cutting force with low feed rate [10]. Thus, better surface quality can be achieved with an optimum combination of cutting parameters such as cutting speed, feed rate and depth of cut [11]. Numerous experiments are necessary to determine optimum experimental conditions with conventional methods. It is not possible to see the effect of experiment variables on each other on the optimum experimental conditions with the obtained results [12].Therefore, experiment design methods are used to determine which of the multiple factors affecting the product properties are more effective on the product [12, 13].When the experimental design is used to determine the optimal values of the variables, there are basically two important gains. The first is the ability to determine the process success-variable relationship by performing a few designed experiments compared to the previous method. Thus, both time and economically significant gains are achieved. Secondly, since the data to be obtained are evaluated statistically, it is possible to better understand the process and to make better decisions by accurately determining the interactions among the variables [14].

2. RESPONSE SURFACE METHOD

One of the available methods based on statistical is Response Surface Methods (RSM) [15, 16]. RSM was developed and described by Box and Wilson in 1951. First, it was applied to the chemical industry [17]. RSM is widely used in the formulation of a new product, in the improvement of existing product design, in process optimization, development and improvement of process [11]. The RSM demonstrates an experimental setup aimed at achieving the maximum number of dependent variables on the response surface with the smallest number of observable values possible [15, 16]. The main purpose of the RSM is to estimate the region and the optimum point of the region that provides the desired characteristics in a design consisting of many factors that are effective on the result in an experimental study[15]. RSM includes experimental strategies to investigate the experimental space of process variables and optimization techniques using experimental modelling techniques used to determine the relationship between the response of the system and the independent variables acting on it [4, 11, 15, 17, 18]. The solution of multi-response problems is evaluated in two stages, namely modelling and optimization after the data is obtained.In describing the problem, characteristics are used, which are considered as input variables $(X_i, i=1, 2, ..., k)$ and response variables $\left(Y_j, j=1, 2, ..., r\right)$ [19].

In the process of modelling multi-response surface problems, it is necessary to determine an appropriate function to define the relationship between response variables and input variables. Given that the response surface problems in the real world are nonlinear, we use regression analysis based on second order polynomial models in determining the predicted response functions [3]. The degree to which the interaction of a factor's main effect or other factors has a significant effect on the value of the response variable is determined by means of regression coefficients [20].

Since the form of the act ual response function is unknown, an appropriate approach should be found for the real functional relationship among the response and independent variables. If the response of the system is a good fit as a linear function of the independent variable, then the approach is a first degree model.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \varepsilon \quad (1)$$

If there is a curvature on the response surface of the system, a second degree model may be more appropriate;

$$y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x^2{}_j + \sum_{i}^{k-1} \sum_{j}^{k} \beta_{ij}\, x_i x_j + \varepsilon \quad (2)$$

In this equation; y response variable, β_0, β_1, β_2,,…β_k unknown regression parameters, x_i, x_jprocess (decision) variables (*i=1, 2, …, k*) and (*j=1, 2, …, k*), and ε error term [21].

Most used RSM; Central Composite Design (CCD) and Box-Behnken design [20]. The Box-Behnken experimental design method requires fewer experimental/numerical results than the full factorial experimental design method [22] Box-Behnken designs a type of rotational designs, were developed by Box and Behnken in 1960, from three-level incomplete multi-factor designs used in predicting second-degree model parameters. Each factor in Box-Behnken designs has three levels. Box-Behnken designs are a more economical design class than CCDs[23]. Box-Behnken designs are a response surface design that is used for predicting models at second degree, for setting up sequential designs, for analyzing the lack of confidence in the model, and for allowing blocks [24] and is being used effectively in experimental designs.

3. EXPERIMENTAL STUDY

In this study, a three-level Box-Behnken design combined with response surface methodology was used to optimize cutting parameters such as feed rate, cutting speed and depth of cut, which affect the surface roughness of the AISI 1040 steel commonly used in the industry. The steps of the experimental study for optimizing the cutting parameters affecting the surface roughness are shown in Figure 1.

Initially, samples were prepared at ø70 mm and 200 mm length from the AISI 1040 steel. In the experiments to be done, Sandvik DDJNR 2525M15 was used as tool holder, DNMG 150608 diamond cutting insert was used as cutting tool.The "ACE Micromatic Designers LT-20C CNC" lathe was used in the machining of the samples. The Box-Behnken design was preferred for the experimental design in this study. Because in this design, the alpha value used in determining the number of experiments and the experiment parameters is 1, so it is easier to design. Box-Wilson design changes the parameters for the different experiments one by one, whereas Box-Behnken design can be changed more than one parameter for different experiments at the same time. For this reason, Minimum number of experiments in the experimental designs formed with RSM is obtained by Box-Behnken design. As is the case with this experimental study, the number of experiments in Box-Wilson designs is 20 for 3-level designs, while that in Box-Behnken design is 15. After the experimental design to be used in the study is determined, the cutting parameters and levels affecting the surface roughness are determined and given in Table 1.

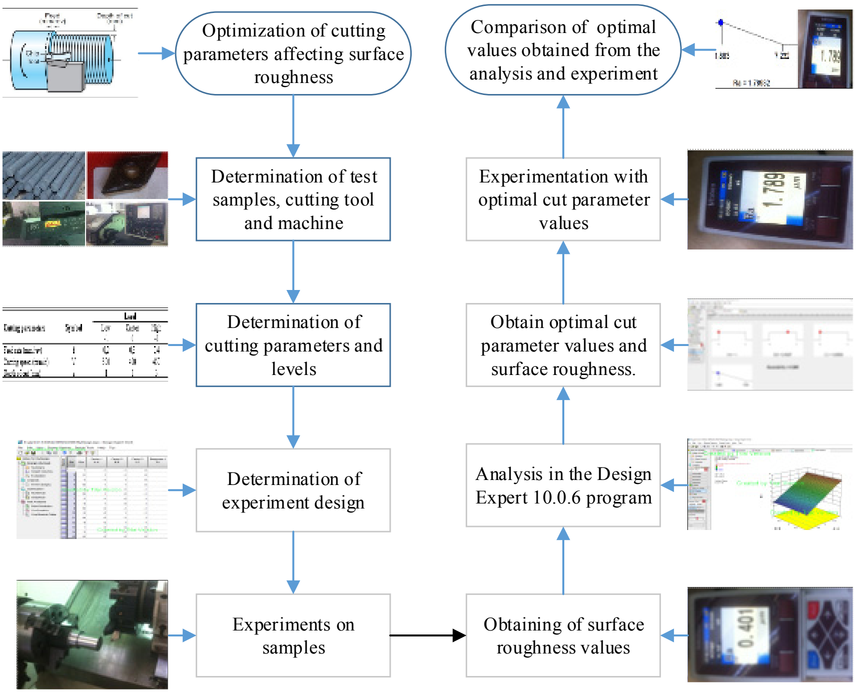


Figure 1. Experimental study steps

Table 1. Cutting parameters and levels

Cutting parameters	**Symbol**	**Level**		
		Low -1	**Center 0**	**High +1**
Feed rate (mm/rev)	*f*	0.2	0.3	0.4
Cutting speed	*V*	300	400	450
Depth of cut (mm)	*a*	1	2	3

The number of experiments to be done according to the Box-Behnken design was determined as 15 experiments. Experiments were carried out with the experimental set and surface roughness values obtained by the experiments were measured with "Mitutoyo Surftest SJ-210" surface roughness meter and given in Table 2. The values given in Table 2 show both the 3 levels used in the Box-Behnken design and the actual values corresponding to these levels.

Statistical analyses were carried out using the Design Expert 10.0.6 package program for the obtained experimental responses and a second-degree regression model appropriate for optimum surface roughness was constructed as in equation (3).

Table 2. Box-Behnken experiment design and experiment results

Run no	Actual and coded level of variables			Experimental response
	Feed rate, f (mm/rev)	Cutting speed, V (m/min)	Depth of cut, a (mm)	Surface Roughness, Ra (µm)
1	0.2 (-1)	300 (-1)	2 (0)	1.918
2	0.4 (+1)	300 (-1)	2 (0)	6.769
3	0.2 (-1)	400 (+1)	2 (0)	1.883
4	0.4 (+1)	400 (+1)	2 (0)	6.686
5	0.2 (-1)	350 (0)	1 (-1)	1.887
6	0.4 (+1)	350 (0)	1 (-1)	6.968
7	0.2 (-1)	350 (0)	3 (+1)	2.103
8	0.4 (+1)	350 (0)	3 (+1)	7.232
9	0.3 (0)	300 (-1)	1 (-1)	4.258
10	0.3 (0)	400 (+1)	1 (-1)	4.162
11	0.3(0)	300 (-1)	3 (+1)	4.483
12	0.3 (0)	400 (+1)	3 (+1)	4.546
13	0.3 (0)	350 (0)	2 (0)	4.381
14	0.3 (0)	350 (0)	2 (0)	4.326
15	0.3 (0)	350 (0)	2 (0)	4.233

$$R_a = +4.31 + 2.48f - 0.019V + 0.14a - 0.012fV + 0.012fa + 0.040Va + 0.093f^2 - 0.092V^2 + 0.14a^2 \quad (3)$$

Variance analysis (ANOVA) was performed to determine the contribution of the cutting parameters to the output parameters and the results of the quadratic model variance analysis are given in Table 3.

Table 3. ANOVA table for surface roughness

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	49.63	9	5.51	521.96	< 0.0001	significant
f-Feed rate	49.32	1	49.32	4669.09	< 0.0001	Significant
V-Cutting speed	0.00285	1	0.00285	0.27	0.6256	
a-Depth of cut	0.15	1	0.15	14.03	0.0133	significant
fV	0.00057	1	0.00057	0.055	0.8246	
fa	0.00057	1	0.00057	0.055	0.8246	
Va	0.00632	1	0.00632	0.60	0.4742	
f^2	0.033	1	0.033	3.02	0.1427	
V^2	0.03	1	0.03	2.98	0.1450	
a^2	0.076	1	0.076	6.97	0.0460	significant
Residual	0.051	5	0.01			
Total	49.68	14				

Adequate precision = 63.806
R^2 = 0.9989, R^2 (predicted) = 0.9861, R^2 (adjusted) = 0.9970

The large value of the coefficient of multiple determination (adjusted R^2 = 0.9970) indicates that 99.70% of the variance in the response can be explained by the quadratic model in Table 3. The large F-value of the model (521.96) implies the great significance ($p< 0.0001$) of the regression model. The associate p-values less than 0.05 indicate that the model terms are statistically significant. The ratio of 63.806 of the adequate precision shows an adequate signal.

The observed (experimental) results and the predicted values obtained using these model equations for surface roughness are given in Figure 2. It could be observed that the predicted values are in agreement with the experimental results, which indicates that the developed regression quadratic models can be accurately used to calculate the response factors at any given variable in the interval of our experimental design.

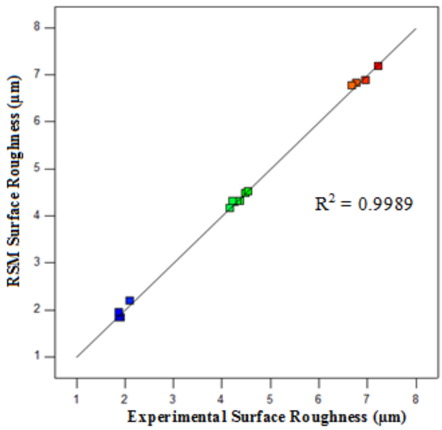


Figure 2. RSM versus experimental predicted surface roughness

Then, the effects of the cutting parameters on the surface roughness were investigated and the obtained findings are given in Figures 3-5. Accordingly, the effect of the feed rate and the cutting speed on the surface roughness is shown in Figure 3.

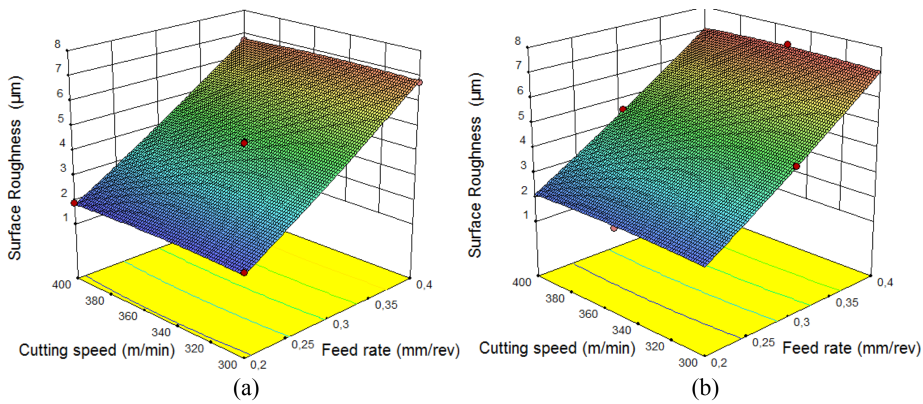
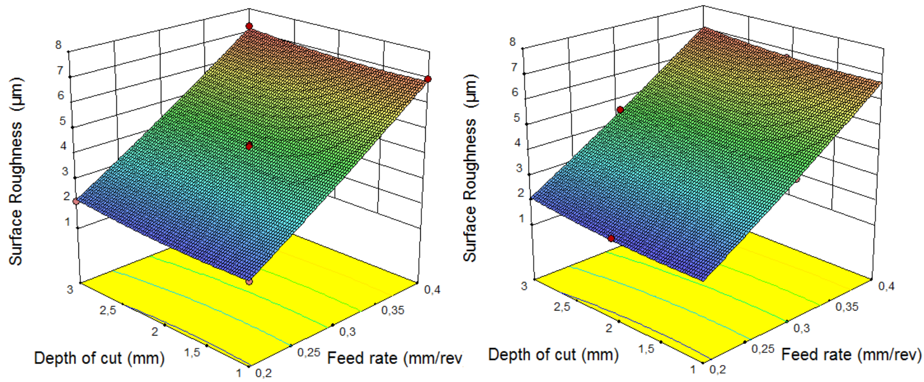


Figure 3. Effect of feed rate and cutting speed on surface roughness

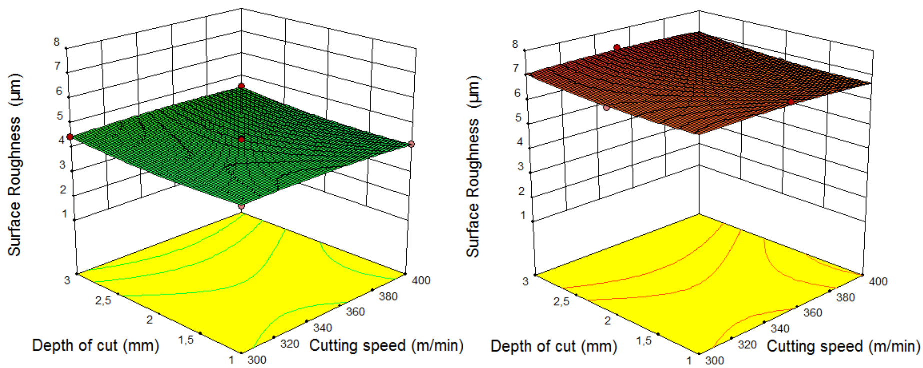
Examining Figure 3a, it appears that the feed rate on the surface roughness is a significant effect. Accordingly, it is seen that the surface roughness increases seriously when the feed rate is increased. Despite this excessive effect of the feed rate, it has been found that the cutting speed is not a very significant effect on the surface roughness. It is also observed that increasing the depth of cut parameter (Figure 3b) increases the surface roughness by keeping the feed rate and cutting speed parameters constant. The effect of depth of cut and feed rate parameters on surface roughness is given in Figure 4.



(a) (b)

Figure 4. Effect of Depth of cut and feed rate on surface roughness

Figure 4a shows that surface roughness increases when both the depth of cut and feed rate parameters are increased. However, it is understood that the effect of the feed rate parameter is greater. In Figure 4b it is seen that when both parameters are held constant and the value of the cutting speed parameter is increased, there is a slight decrease in surface roughness.The effect of depth cut and cutting speed parameters on surface roughness is shown in Figure 5.



(a) (b)

Figure 5. Effect of depth of cut and cutting speed on surface roughness

Figure 5a shows that when the depth of cut parameter increases the surface roughness increases but when the cutting speed parameter increases, the surface roughness decreases. In Figure 5b, when both parameters are held constant and the feed rate value is increased, surface roughness appears to increase significantly.

After examining the effects on the surface roughness of the cutting parameters, optimum cutting parameter values for minimum surface roughness have been obtained from the program of Design Expert 10.0.6. The optimum cutting parameter values obtained and the surface roughness value corresponding to these optimum values are given in Table 4.

Table 4. Optimum cutting parameters and surface roughness values

Feed rate f (mm/rev)	Cutting speed V (m/min)	Depth of cut a (mm)	Surface Roughness Ra (μm)	Desirability
0.2	397.58	1.5617	1.7893	0.984

According to these optimum cut parameter values, 3 samples were prepared and re-experiments were carried out. As a result of the experiments, surface roughness values were measured and the average surface roughness was obtained as 1,791 μm. In this case, it can be said that the results obtained from the Box-Behnken design and experimental study are compatible.

4. CONCLUSION AND EVALUATION

In this study, three-level Box-Behnken design combined with response surface method is aimed at optimization of cutting parameters affecting surface roughness. For this, 15 samples with Ø 70 mm and 200 mm length were prepared and surface roughness values were measured by machining on a CNC lathe. The obtained surface roughness values were analyzed in Design Expert 10.0.6 program and the cutting parameters affecting the surface roughness were optimized. The following findings were obtained according to the results obtained from this study.

- The results of the Box-Behnken design were obtained as R^2 (adjusted) = 0.9970, and it was found that this design could make accurate estimates for this problem.
- According to parameters and parameter levels used in the experiments, it is found that the feed rate is the most important parameter affecting surface roughness.
- From the cutting parameters of the model, it can be seen that the cutting speed has the least effect on the surface roughness.
- For the optimization of surface roughness value, it is necessary to use feed rate 0.2 mm/rev, cutting speed 397.58 m/min and depth of cut 1.5617 mm.
- The optimum surface roughness values obtained from the Box-Behnken design and the experimental study are very close to each other, and thus the Box-Behnken design can be used to solve the problems of optimization of surface roughness.

In addition, in future work to optimize cutting parameters, the use of fuzzy response surface methods will allow the results to be more precise.

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