Optimization of wood surface machining parameters in CNC routers: Response surface methodology (RSM) approach

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ABSTRACT

The prediction of optimal machining conditions for wood surface quality play a very important role in process planning for furniture industry. In this study a mathematical model was developed to predict the surface roughness and to determine optimal machining condition of European Black pine (*Pinus nigra Arnold*). Design of experiment was used to study the effect of CNC machining parameters such as spindle speed, feed rate and depth of cut on arithmetic average roughness (Ra). The optimization process was adopted by a combined approach of central composite face-centered (CCFC) experimental design and response surface methodology (RSM). The second order mathematical models in terms of machining parameters were developed for surface roughness using response surface methodology. The results indicate that the most effective parameters were found in the interaction between feed rate and spindle speed, and their contribution to the model value was 62.41 % on the surface roughness. To achieve the minimum surface roughness, the optimum values obtained for spindle speed, feed rate and depth of cut were 18000 rpm, 2 m/min and 2.646 mm, respectively.

Keywords:*Surface roughness,optimization,response surface methodology (RSM),wood material,design of experiment (DOE)*

I. INTRODUCTION

Wood surface roughness is a problem of quality characteristics of wood material. This problem depends on some factors such as anatomical structure, moisture, hardness, density, annual ring variation, cell structure of early-late wood ratio and machining conditions [1-2]. CNC wood working machinery has been widely introduced in the wood industries, especially in the furniture industry. CNC has been used for grooving, milling and pattering of furniture materials. This technology presents many advantages such as reduced production time, increasedproductivity, reduced production cost and improved surface coating performance [3]. However,selection of optimum machining parameters is a crucial step for providing better surface quality for furniture industry. Therefore, the optimum cutting parameters and the parameter analysis can be determined by systematic way. Design of experiment is successful method to determine parameter analysis and optimum processing variables. Traditional experimental design needs a long time because of the number of experiments. For this reason, advanced experimental design is required to reduce the number of experiments.

In recent years, design of experiment techniques such as response surface method, full factorial design, Taguchi and robust design have been used to various engineering and machining problems [5-8]. These methods are used to determine the optimum machining parameters.

The studies in literature related to CNC machining is summarized as follows:

Davim et al. [9]studied the influence of cutting parameters such as cutting speed and feed rate on surface roughness of MDF (medium density fiberboard) milling. According to the results the surface roughness decreased with the increase of spindle speed and increased with the feed rate. The milling test showed the important factor that spindle speed indicated on the surface roughness.

Lin et al. [10]investigated the machinability of MDF by passing a cutting tool through it at relatively low speed. These authors reported that unrefined particles play a major role during machining. The board densities were found to have a major influence on the machinability characteristics such as surface roughness.

Norazmein et al. [11] studied the development of predicted mathematical model for cutting force (Fc) during side milling of MDF using uncoated carbide insert. Response surface method (RSM) and Box-Behnken design (BBD) were used to establish the cutting force model. The machining parameters were spindle speed, feed rate and routing width. They reported that lower cutting force could be obtained with higher cutting speed, lower feed rate and lower routing width.

Sofuoglu[12] investigated that optimization of CNC machining parameters such as cutter type, tool clearance strategy, spindle speed, feed rate and depth of cut were examined using Taguchi method on the surface quality of massive wooden panels made of Scots pine (*Pinussylvestris*L.). ANOVA analysis was used to determine significant factors affecting the surface roughness (Ra and Rz).Optimal cutting performance for Ra and Rz was obtained for cutter 1, at a tool clearance strategy of a raster 16,000 rpm spindle speed, 1000 mm/min feed rate and depth of 4 mm.

Jafarian et al. [13] evaluated the optimum cutting conditions on surface roughness and tool life in Inconel 718 machining. They used the intelligent methods including ANN and MOO in order to optimum surface roughness and tool life. It was shown that for each cutting parameter, increase in the MT leads to higher surface roughness value.

Hassanpour et al. [14] investigated the effects of various cutting conditions on the surface integrity of titanium part (Ti6A14V) in the micro milling process. According to results the variation of cutting speed as one of the significant factors decreased cutting force and provided better surface quality

Ramesh et al. [15] used the response surface methodology for minimizing the surface roughness in machining titanium alloy. It was found that surface roughness increased with increasing feed rate, but decreased with an increasing cutting speed and depth of cut. In addition to these, the predicted results were fairly close to experimental values.

II. MATERIALS AND METHODS

Material Used

European Black pine (*Pinus nigra Arnold*), species with intensive use in the furniture industry were selected for the study. The samples were prepared with the dimension of 140 mm x 50 mm x 18 mm for each procedure. Density level of Black pine wood was measured randomly through 60 samples. Each sample was weighed and its dimensions were measured at an accuracy level of 0.1 g and 0.01 mm, respectively. Samples were conditioned in a climate room having a temperature of 20°C and relative humidity of 65% until they reach a moisture content of 9±1%. The density of the wood was measured as 0.73 g/cm³ [16-17].

Machining Conditions and Roughness Measurements

The samples were processed with 3-axis CNC router with 5.5 kW spindle power, a maximum spindle speed of 20000 rpm and a maximum feed rate of 10 m/min. Roughness measurement device is a stylus-based portable profilometer that is Sutronic-25 type equipment. Diamond stylus with a 5(μm) radius and 90° of tip angle was employed for roughness measurement. According to ISO 4287, there are two accepted roughness parameters, namely average roughness (Ra*)* and mean peak to valley height (Rz). In this study Ra calculated from digital information from the surface of sample was used to evaluate the surface quality of the samples [18-20].

Response Surface Methodology (RSM)

RSM was developed by Box and Draper (1984). This method is a collection of mathematical and statistical techniques. Central composite design (CCD) is an experimental design used to achieve determine optimum process parameters for a minimal number of experiments [21]. This method is useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize the response. In this study, composite face-centered (CCFC) design was used to determine the optimal conditions for feed rate, spindle speed and depth of cut. Selection of independent variables and their ranges, experiments were established based on a CCFC design with three factors at three levels and each independent variable was coded at three levels between -1, 0 and +1. The experimental design used for this work is shown in Table 1.

Table 1: CNC procedure parameters and levels applied in CCFC design

Symbol	Parameters	Unit	Level (-1)	Level (0)	Level (+1)
n	Spindle speed	rpm	12000	15000	18000
f	Feed rate	m/min	2	5	8
d	Depth of cut	mm	2	4	6

In this study, total number of 20 experiments (consisting of 8 cube points, 6 central points and 6 axial points) were carried out (Table 2). The total number experiments were calculated from the following equation:

$$N=2^{n} + 2n + n_c \quad (1)$$

Where *N* is the total number of experiments required; *n* is the number of factors; and *c* is the number of center points. The experimental sequence was randomized in order to minimize the effects of unexpected variability in the responses due to extraneous factors. A second-order polynomial equation was used in order to develop an empirical model which correlated the responses independent variables. The general form second order polynomial equation is:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_i \sum_j^k \beta_{ij} X_i X_j + \epsilon \quad (2)$$

According to equation (2) Y is the predicted reaction or reactions (Ra), X_i and X_j are variables, β_0 a constant, $\beta_i \beta_{ii}$ and β_{ij} are respectively the first, the second degree coded input parameters and parameter interactions of linear, quadratic and the second-order terms, respectively and *k* is the number of independent parameters (k=3 in this study) and ϵ is the error term.

Table 2: CCFC design and results for Ra

RunOrder	Feed Rate (*f*,m/min)	Spindle Speed (*n*,rpm)	Depth of Cut (*d*,mm)	Roughness (Ra,µm)
1	8	18000	2	17.05
2	2	18000	2	5.78
3	8	18000	6	19.36
4	2	12000	2	11.84
5	5	15000	4	9.82
6	5	15000	2	10.81
7	5	12000	4	7.54
8	2	18000	6	10.41
9	5	15000	4	10.42
10	5	15000	4	10.05
11	8	15000	4	13.58
12	8	12000	2	6.64
13	5	15000	6	13.87
14	5	18000	4	9.53
15	2	15000	4	11.91
16	2	12000	6	16.81
17	5	15000	4	10.14
18	8	12000	6	8.26
19	5	15000	4	9.88
20	5	15000	4	9.56

III. RESULTS AND ANALYSIS

Developmentthe Model

Due to the fact that the term R^2 which denotes prediction accuracy of the regression equations of roughness is greater than 90% of all the reaction values are within reliable interval, closest to the actual values. In Table 3, indicating correlation of the experimental roughness value and the estimated values from the regression equation are shown. The experimental data were analyzed by the polynomial models such as linear, 2-way interaction and full quadratic models. The adequacy of models performed indicated that linear, interaction and quadratic models had lower *p*-value (<0.05). As shown in Table 3 shows the R^2 and Adjusted-R^2 values were found low in linear and interaction models. Thus, the linear and interaction models cannot be chosen for modeling of experimental data. However, quadratic model was calculated to have maximum R^2 and R^2-adjusted and the models had low *p*-value. Hence the quadratic model was chosen for in this study.

Table 3: Regression model

Regression model	R^2	Adj-R^2	
Linear Ra (µm) = $0.97 + 0.271 f + 0.000368 n + 0.829 d$	20.05%	5.06%	
Linear + square Ra (µm) = $-37.9 – 2.14 f + 0.00717 n – 2.70 d + 0.241 f^2 – 0.000000 n^2 + 0.441 d^2$	35.06%	5.08%	
Linear + interaction *Ra* (µm) = $34.34 - 6.33 f – 0.002020 n + 1.31 d + 0.000472 f*n – 0.1181 f*d – 0.000007 n*d$	84.20%	76.91%	
Full quadratic Ra(µm) =$-4.47 – 8.743 f + 0.004784 n – 2.217 d + 0.2410 f^2 - 0.000001 n^2 + 0.4409 d^2 + 0.000472 f*n – 0.1181 f*d – 0.000007 n*d$	99.21%	98.50%	suggested

Variance Analysis (ANOVA)

Table 4 indicate the ANOVA conducted for Rα.The *p*-value serves as a tool for checking the significance of each coefficient. Value of *"prob>F"* are less than 0.05 indicating that the model term are significant. In this case *f, n, d,* f^2, n^2, d^2, *fd, fn*are significant factors.These model shows that lack-of-fit error is insignificant indicating that the fitted model is accurate enough to predict the response. Contribution (PC %) of each factor on the total variation is specified as percentage. Accordingly the most effective parameter for Ra is in interaction between feed rate and spindle speed having a value of 62.41 %. The coefficient of determination (R^2) for the suggested model was 99.21 % (as the closer the R^2 value is, the better the models fit the experimental data). The suggested model explained 99.21 % of the variability in the response. The "pred-*R*-squared" of 0.9604 is in reasonable agreement with the "Adj*R*-squared" of 0.9850 in which the difference is less than 0.1.

Table 4:ANOVA of CCFC design for Ra

Source	DF	Contribution % (PC)	SS	MS	*F*-Value	*P*-Value
Model	9	99.21	229.304	25.478	139.89	0.000
Linear	3	20.05	46.337	15.446	84.80	0.000
f	1	2.87	6.626	6.626	36.38	0.000[a]
n	1	5.27	12.188	12.188	66.92	0.000[a]
d	1	11.91	27.523	27.523	151.11	0.000[a]
Square	3	15.01	34.688	11.563	63.48	0.000
f^2	1	8.67	20.040	12.933	71.01	0.000[a]
n^2	1	2.64	6.094	11.460	62.92	0.000[a]
d^2	1	3.70	8.554	8.554	46.96	0.000[a]
2-Way Interaction	3	64.16	148.279	49.426	271.38	0.000[a]
*f * d*	1	1.74	4.019	4.019	22.06	0.001[a]
*n * d*	1	0.01	0.015	0.015	0.08	0.778
*f * n*	1	62.41	144.245	144.245	791.98	0.000[a]
Error	10	0.84	1.821	0.182		
Lack-of-Fit	5	0.60	1.385	0.277	3.18	0.115
Pure Error	5	0.19	0.436	0.087		
Total	19	100	231.125			

DF: degrees of freedom, PC: percentage contribution, SS: Sum of squares, *F*: *F*-test value and *P*:error variance [a] At a given response, parameters belonging to the filled cells are effective within 95 %reliability interval.

Model Checking

In order to check the data for normality, it is best to construct an NPP (Normal Probability Plot) of the residuals. Residual is the mean difference between the observed value and the predicted value. Figure 1 **a** shows that the residuals generally fall on a straight line implying that the errors were disturbed normally, meaning was the experimental data come from a normal population. Figure 1 **b** shows plot of the residuals versus the fitted values for the surface roughness data. As the result of the residuals no unusual structure was apparent.

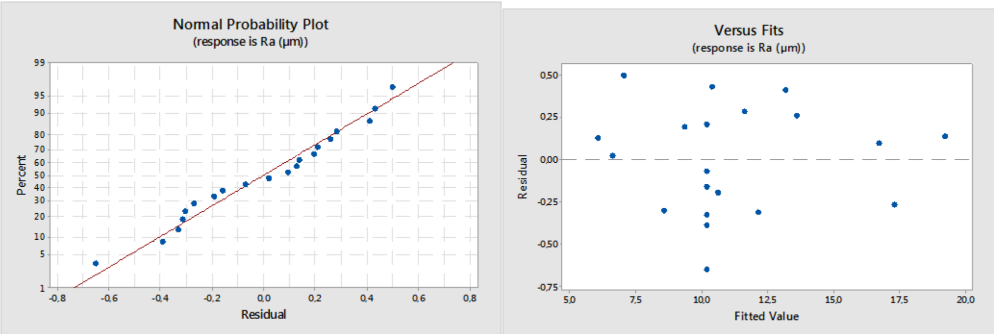
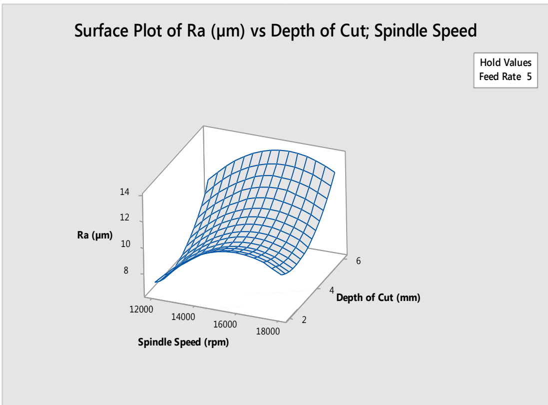


Fig. 1.aNPP of residuals for the surface roughness**b** Plot of residuals versus fitted values

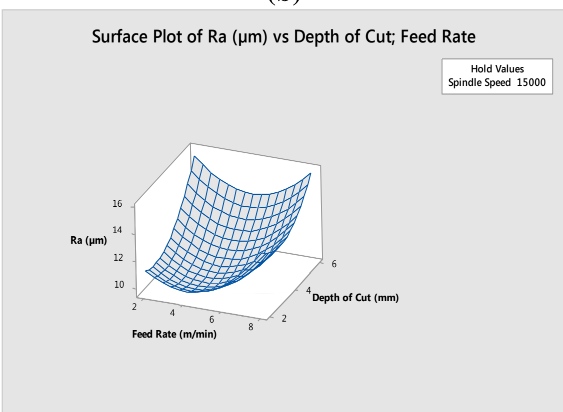
Surface Graphs and Analysis

Figure 2 **a** shows the interaction plot between surface roughness and spindle speed with respect to depth of cut.If the depth of cut increases, the surface roughness value increases. As the spindle speed decreases from 16000 to 12000 rpm, the surface roughness value is reduced.Figure 2 **b** shows the interaction plot between surface roughness and feed rate with respect to depth of cut. If the depth of cut increases, the surface roughness value increases. When the feed rate increases from 4 to8 m/min, the surface roughness value is increases. Figure 2 **c**shows the interaction plot between surface roughness and feed rate with respect to spindle speed.Interaction effect of feed rate and spindle speed on the surface roughnessare depicted. It is noticed that at a lower and higher spindle speed, the change in feed rate significantly affect the surface roughness.

(a)



(b)



(c)

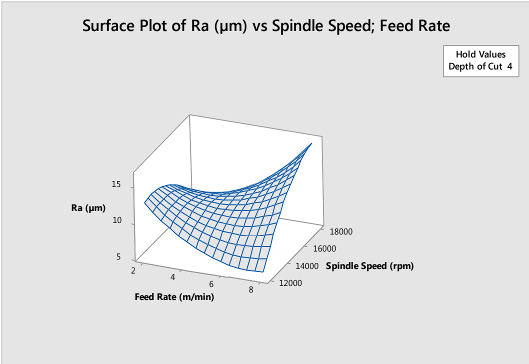


Fig.2. (a) Surface plot representing the influence of spindle speed and depth of cut. **(b)** Surface plot representing the influence of feed rate and depth of cut. **(c)** Surface plot representing the influence of feed rate and spindle speed.

Parameter Optimization

Minitab desirability function plot is an ideal technique for determination of these optimum machining parameters. Table 5 shown that the target set, the lower limits, the upper limits and target value are given. From the analysis results, the optimization value was obtained as 5.564 µm for the Ramodel as shown in Fig 3. Optimal machining parameters for minimizing surface roughness were obtained spindle speed of 18000 rpm, feed rate of 2 m/min and depth of cut 2.646 mm. Moreover, the desirability value 1 for Ra where also the desirability value can be seen 1 or close to 1.

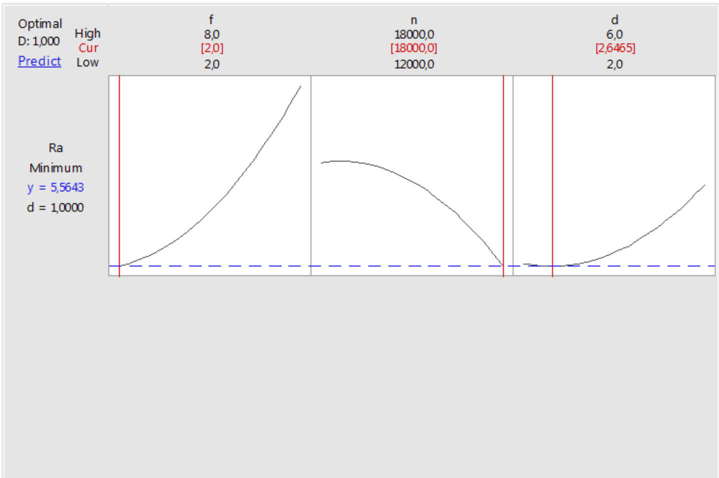


Fig. 3. Response optimization plot for Ra

Confirmation Test

The predicted values and measured experimental values were compared. The comparison of experimental results-predicted values are shown in Table 5.Comparison results from evidence that predicted values for response value is close to experimentally obtained values. The error percentage is 0.69 %. So, the mathematical model can be successfully use to predict the Ravalue for any combination of the feed rate, spindle speed and depth of cut within the range of the performed experimentation.

Table 5: Optimal CNC machining parameters for Ra

Response	Target	Optimal conditions			Lower	Target	Upper	Pred.	Exp.	Error (%)
(Ra, µm)		*f* (mm/min)	*n* (rpm)	*d* (mm)						
Ra	Min.	2	18000	2	5.78	5.78	19.36	5.740	5.780	0.69

IV. CONCLUSION

In this work, effect of machining of Black Pine wood, the surface roughness characteristics were investigated. The optimization process was adopted by a combined approach of experimental design and response surface methodology. The results is summarized as follows:

- The results were analyzed using 3D surface graphs. The surface graphsdemonstrated the parameterinteractions were highly effective on machined surface roughness.
- Analysis of variance (ANOVA) demonstrates that the surface roughness (Ra) was influenced by interaction between feed rate and spindle speed with PCR of 62.41 %.
- Mathematical models were developed using response surface methodology to formulate the input feed rate, spindle speed and depth of cut to the Ra. Confirmation experiments show that the developed mathematical models with RSM can be used machining of CNC turning. The error percentage is 0.69 %.
- Selected mathematical model showed that the developed RSM model is statistically significant and suitable for all the machining condition in order to higher R^2 and R^2-adjusted values.
- Based on the response surface optimization and the desirability method of RSM, the optimal machining parameter of CNC turning are found to be as follows: feed rate of 2 m/min, spindle speed of 18000 rpm and depth of cut of 2.646 mm. The optimized surface roughness value is Ra=5.564 µm.

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