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Mathematical Modelling of Surface Roughness on Tropical Wood Machining using Response Surface Methodology.

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Abstract. Surface roughness is an important indicator to assess the surface processing quality and has a decisive impact on the furniture finishing effects. In this research, the application of response surface methodology (RSM) has been carried out for modelling and analysing of influences in the sanding process on wood materials. Surface roughness parameter R_a showed surface characteristics of Tembesu, Jati and Petanang. This study is aimed to observe the effect of feed rate and grit size on R_a. The central composite design (CCD) was used as a design of experiment (DOE). There were 8 runs at factorial points and additional 5 replicated runs at the centre point. The sanding process was done using a modified horizontal milling machine. The results are statistically analysed by using Design Expert software. It was found that increasing of feed rate had a positive effect on the roughness value of R_a and greater feed rates increased the surface roughness. On the other hand, grit size influenced negative effect. Larger grit size affected the smoother surface roughness. At the end of this study, it was also revealed that the optimum machining conditions in terms of feed rate and grit size were 17 mm/min and 240 for Tembesu and Jati, while Petanang was 18.63 mm/min and 226.52.

Introduction

Surface roughness is an important parameter to assess the surface processing quality of the object and has a decisive impact on the furniture finishing effects. Domestic and foreign scholars have had a lot of studies on determination method and influencing factors of surface roughness [1]. The surface quality of solid wood products is one of the most important properties influencing further manufacturing processes such as finishing or strength of adhesive joints. Laminated lumber with smoother surfaces will have a better glue line, resulting in higher strength properties. Surface roughness of wood can be affected by various factors such as annual ring variation, wood density, cell structure, and late wood/early wood ratio. Type of machining used during production, raw material characteristics of a work piece or a combination of both these parameters is responsible for surface quality of the final products and determining its cost. Increased cutting speed or RPM results in an improved surface quality of wood products [2]. In recent years, the wood machining has acquired great importance due to the short supply of wood and increasing environmental awareness among users and manufacture [3].

In order to know surface quality and dimensional properties, it is necessary to employ theoretical models for prediction purpose [4]. They developed a mathematical model to predict the surface roughness of machined glass fibre reinforced plastic (GFRP) work piece using response surface method. Analysis of variance (ANOVA) is used to check the validity of the model. Other researchers [5] and [6] investigated the use of RSM in developing a surface roughness model for machining mild and hardened steel. The latest research in wood machining was reported by [7]. They have proven that the artificial neural network prediction model is a useful, reliable and quite effective tool for modelling surface roughness of wood.

A few years ago, a similar study was conducted by [8], they investigated the effects of crucial variables in achieving the desired sanded surface quality at optimum condition and wood surface evaluation. This evaluation was inspired from the study carried out by [9] and [10], which was recognized the need for a quality control of the roughness of machined wood surface in compliance with an accepted standard.

However, no such standard has been developed for wood surface. Therefore, in this study, the lack of such information on sanding off Tembesu (Fagraea fragrans roxb), Jati (Tectona grandis L.f), and Petanang (Dryobalanops oblongifolia dyre) will be investigated.

Methodology

Wood samples used were Tembesu (Fagraea fragrans roxb), Jati (Tectona grandis L.f), and Petanang (Dryobalanops oblongifolia dyre). The woods are a local timbre business in South Sumatera, Indonesia. The samples were prepared according to [11]. Sanding process was conducted at a constant speed 2500 RPM using a horizontal milling machine that was attached with independent motor. This study used feed rate (*f*) and grit size as input parameter of the models. The output parameters are the value of surface roughness parameter R_a (arithmetic mean). All samples were sanded in parallel direction to the wood fibre using three levels of feed rate 17 mm/min, 25.5 mm/min, and 34 mm/min. The samples were sanded using sand paper that contains aluminium oxide abrasive that was anchored with resin and different types of abrasive grit size 120, 180, and 240, at a depth of cut of 1.5 mm. Each measurement has been repeated three times and the average values are tabulated for the analysis.

One of the main advantages of the stylus method is to have an actual profile of the surface and standard numerical roughness parameters, which can be calculated from the profile. Any kind of irregularities and magnitude of roughness of a surface can be objectively quantified by this method. This method was investigated by [16] in comparison to 3D scanning. They revealed that these two different methods showed a good agreement with each other. Based on their findings in their work, it appears that both methods can be successfully used to evaluate and to get objective numerical values on surface quality. Therefore, in this study a fine stylus method was employed to determine surface roughness of machined wood samples prepared from two species [2]. A surface roughness tester, *Accretech Handysurf* E-35 A/E (Japan), was used to measure surface roughness values. This tester uses a stylus with measuring speed 0.6 mm/s, evaluation length 12.5 mm and cut off 2.5 mm.

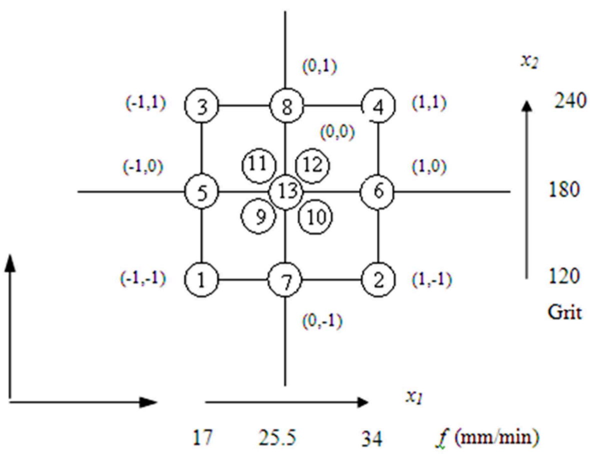


Fig. 1. Design of Experiments (DOE)

Based on the DOE shown in Fig. **1**, the CCD comprised of 13 runs with 5 replicated runs at the centre was carried out for any type of woods. The statically analysing of resulted data was accomplished according to RSM [12] and was calculated using software Design Expert 8.0.7.1.

Results and Discussions

The results are presented in Table 1. Based on these results, the empirical mathematical models are generated.

These models used no transformation and were analysed by means the ANOVA for checking an adequacy of the resulted equations. The empirical mathematical models for R_a in terms of coded factors are shown in following equations:

$$R_a = 3.3376 + 0.1633\,x_1 - 0.3417\,x_2 + 0.0134\,x_1^2 + 0.0984\,x_2^2 + 0.0125x_1x_2 \quad (1)$$

$$R_a = 4.22 + 0.30\,x_1 - 0.65\,x_2 - 0.014\,x_1^2 + 0.021\,x_2^2 + 0.057x_1x_2 \quad (2)$$

$$R_a = 3.95 + 0.59\,x_1 - 0.32\,x_2 \quad (3)$$

The Eq. 1, 2, and 3 represented the empirical mathematical models for Tembesu, Jati and Petanang respectively. From these equations, it is clearly to recognise that Eq. 1 and 2 were quadratic, while Eq. 3 was a linear model. It can also be concluded that feed rate contributed significantly to increasing of surface finish. In contrary, increasing the grit size influenced on decreasing of surface roughness value. Similar findings were also revealed by other previous researchers from [13] to [15].

Table 1. Experimental Designs and Results

No	Input variables		Roughness value of Tembesu [µm]	Roughness value of Jati [µm]	Roughness value of Petanang [µm]
	Feed rate [mm/min]	Grit size	R_a	R_a	R_a
1	17	120	3.63	4.53	3.53
2	34	120	3.93	5.23	5.07
3	17	240	2.93	3.32	3.24
4	34	240	3.28	3.79	3.57
5	17	180	3.20	3,89	3.39
6	34	180	3.53	4,54	5.09
7	25.5	120	3.80	4,87	3.47
8	25.5	240	3.10	3,63	3.37
9	25.5	180	3.32	4,19	4.01
10	25.5	180	3.33	4,08	3.81
11	25.5	180	3.37	4,37	4.02
12	25.5	180	3.30	4,25	4.09
13	25.5	180	3.34	4,17	4.63

Table 2. ANOVA for R_a-Tembesu

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob>F	
Model	0.90	5	0.18	311.52	< 0.0001	significant
A-feed rate	0.16	1	0.16	278.18	< 0.0001	
B-Grit size	0.70	1	0.70	1217.25	< 0.0001	
AB	6.250E-004	1	6.250E-004	1.09	0.3320	
A^2	4.995E-004	1	4.995E-004	0.87	0.3825	
B^2	0.027	1	0.027	46.52	0.0002	
Residual	4.028E-003	7	5.754E-004			
Lack of Fit	1.348E-003	3	4.493E-004	0.67	0.6132	not significant
Pure Error	2.680E-003	4	6.700E-004			
Cor Total	0.90	12				

As mentioned above, the adequacy of mathematical models was validated using ANOVA that describe the lack of fit and the significance of models as presented in Table 2, Table 3, and Table 4. All of them show that the mathematical models are significant while the lack of fits are not significant. These mean that the models are valid and can be used to analyse the surface quality of these woods sanding processes.

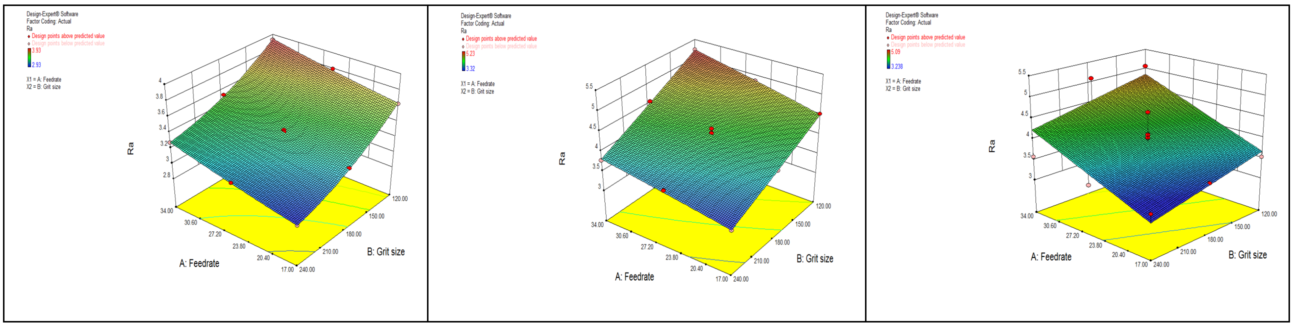
Table 3. ANOVA for R_a-Jati

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob>F	
Model	3.09	5	0.62	85.18	< 0.0001	significant
A-feed rate	0.55	1	0.55	76.12	< 0.0001	
B-Grit size	2.52	1	2.52	347.76	< 0.0001	
AB	0.013	1	0.013	1.82	0.2189	
A^2	5.521E-004	1	5.521E-004	0.076	0.7906	
B^2	1.202E-003	1	1.202E-003	0.17	0.6961	
Residual	0.051	7	7.252E-003			
Lack of Fit	4.686E-003	3	1.562E-003	0.14	0.9338	not significant
Pure Error	0.046	4	0.012			
Cor Total	3.14	12				

Table 4. ANOVA for R_a-Petanang

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob>F	
Model	2.71	2	1.36	6.57	< 0.0151	significant
A-feed rate	2.11	1	2.11	10.24	< 0.0095	
B-Grit size	0.60	1	0.60	2.90	< 0.1194	
Residual	2.06	10	0.21			
Lack of Fit	1.68	6	0.28	2.95	0.1573	not significant
Pure Error	0.38	4	0.095			
Cor Total	4.77	12				

A better observation of Eq. 1, 2, and 3 can be figured out using response surface as shown in Fig**. 2**. The maximum of surface roughness value was indicated by red colour while the minimum was by blue colour. A linear trend was shown in the response surface effect of feed rate while grit size indicated a quadratic trend.



(1) (2) (3)

Fig. 2. Response surface for R_a (1) Tembesu, (2) Jati and (3) Petanang

The next step is to search the optimum condition for sanding with the limit value of feed rate and grit size “in the range”, while surface roughness are set to “minimum”. The iterations resulted in feed rate 17 mm/min and grit size 240, feed rate 17 mm/min and grit size 240, feed rate 18.63 mm/min and grit size 226.52 for Tembesu, Jati and Petanang respectively.

Table 5. Iteration of optimum sanding processes

Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Feedrate	is in range	17	34	1	1	3
B:Grit size	is in range	120	240	1	1	3
Ra	minimize	2.93	3.93	1	1	3

Solutions

Number	Feedrate	Grit size	Ra	Desirability	
1	17.00	240.00	2.93198	0.998	Selected
2	17.16	240.00	2.93484	0.995	
3	17.00	229.43	2.96274	0.967	

3 Solutions found

(1)

Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Feedrate	is in range	17	34	1	1	3
B:Grit size	is in range	120	240	1	1	3
Ra	minimize	3.32	5.23	1	1	3

Solutions

Number	Feedrate	Grit size	Ra	Desirability	
1	17.00	240.00	3.32945	0.995	Selected
2	17.00	239.21	3.33667	0.991	

2 Solutions found

(2)

Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Feedrate	is in range	17	34	1	1	3
B:Grit size	is in range	120	240	1	1	3
Ra	minimize	3.238	5.09	1	1	3

Solutions

Number	Feedrate	Grit size	Ra	Desirability	
1	18.63	226.52	3.22139	1.000	Selected
2	17.29	224.72	3.13725	1.000	
3	17.64	214.50	3.21512	1.000	
4	17.00	219.00	3.14694	1.000	
5	19.31	235.87	3.21948	1.000	

(3)

Conclusions

1. The empirical mathematical models for Tembesu and Jati were quadratic equations, while Petanang was linear equation.
2. The feed rate contributed significantly to increase the value of surface roughness. In contrary, increasing of grit size decreased surface roughness value.
3. Optimum conditions in term of feed rate and grit size, were 17 mm/min and 240, 17 mm/min and 240, 18.63 mm/min and 226.52 for Tembesu, Jati and Petanang respectively.

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