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# An Investigation of the Optimal Cutting Conditions in Parawood (*Heavea Brasiliensis*) Machining Process on a CNC Wood Router

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## ABSTRACT

In this research, series of machining processes of parawood were carried out on a Computer Numerical Control (CNC) wood router to investigate the effect of various machining parameters such as spindle speed, feed rate and depth of cut on the surface quality of parawood machined surface and the wear of the Tungsten Carbide (TC) tool. Using the Design of Experiment (DOE) and statistical methodologies, it was concluded that the optimal cutting conditions for the range of machining parameters studied in this work considering the surface quality are the spindle speed of 12,000 rpm, the feed rate of 180 ipm and the depth of cut of 0.0625 in. In addition, the conditions with the least cutting tool wear was found at the spindle speed of 15,000 rpm, the feed rate of 360 ipm, and the depth of cut of 0.0625 in. The regression model was also obtained to predict the nose width and the surface roughness in each cutting condition. The results provide more understanding on the parawood machining process in order to identify the optimal cutting conditions in which high quality machined surfaces with less surface roughness, less tooling cost, less waste materials, and lower production time are obtained. As a result, the selection of optimal machining parameters can be greatly benefited to the parawood furniture manufacturing industry in terms of productivity improvement.

**Key words:** parawood, surface quality, tool wear, computer numerical control (CNC), tungsten carbide (TC).

## INTRODUCTION

In the past few years, wood machining has often been treated as the last factor on improving productivity as an integrated part in furniture manufacturing; nevertheless, with growing concern on the future supply of wood resources, it becomes significant for researchers to gain a better understanding of wood machining process nowadays. Currently, parawood becomes more popular as an important raw material in Thailand furniture manufacturing industry due to unique properties of parawood such as excellent white wood texture and color like high quality hardwoods. In addition, parawood can be generally obtained from rubber plants which are mostly found in Eastern and Southern of Thailand. Consequently, in order to improve the productivity of using parawood in furniture manufacturing industry, more understanding of parawood machining process and its optimal cutting condition are needed to acquire high quality wood products and to reduce production time with less tooling cost and less waste materials.

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Wood machining is normally performed under very high cutting speed with the extremely sharp cutting edges. It is a predominantly abrasive process, therefore the erosion of the cutting tool material is the main wear mechanism. Low wedge angles are necessary for machining massive wood which generally give a better surface quality; however, the lower the angle the higher the wear (Endler *et al.,* 1999). The amount of wear generally decreases with the increase in hardness, the decrease in grain size and the decrease in binder content of the cutting tool material. Several wear mechanisms may contribute to the overall wear of the cutting tool. Among these wear mechanisms are gross fracture or chipping, abrasion, erosion, microfracture, chemical and electrochemical corrosion as well as oxidation. Corrosion can be easily removed from the cutting edge by abrasion depending on the cutting condition e.g., moisture content, composition, etc. (Sheikh-Ahmad and Bailey, 1999). Some wears could occur through tool edge chipping when wood products which have low moisture content (dry) are machined. Tool life and tool performance in a given operation improve considerably when the Cemented Tungsten Carbides are used in place of either high carbon steel or high speed steels (Bailey *et al.,* 1983).

In general, most research has focused on primary wood production processes needed to produce materials with specific characteristics. There are many different methods to cut materials; routing process is often used to compare different material wear on the cutting tool. There are distinct characteristics in tool wear and surface roughness among different wood fiber plastic products. Differences also exist when these materials are compared to solid wood. A better understanding of the necessary process parameters to cut these materials will lead to the improved results with respect to tool wear and surface roughness (Buehlmann *et al.,* 2001). Researchers have attempted to gain more understanding in wood machining process. The relationship between the cutting process parameters such as feed rate, cutting speed and wood machining productivity was developed (Diei and Dornfeld, 1987). The effects of tool wear, cutting direction, spindle speed on edge chipping of melamine coated particle board using a CNC wood router was studied. The relationship of work piece quality, tool wear and machining conditions was also verified with the empirical monitoring indices. (Rodkwan, 2000).

The investigation of mechanics of machining for other materials, besides metals and wood, such as elastomers were also performed (Rodkwan and Strenkowski, 2003; Strenkowski *et. al.,* 2002, 2003). In their research, the effects of various machining parameters on chip morphology, surface roughness and the associated machining force were examined using the orthogonal cutting test of elastomers. The feed rate and rake angle were found to have significant effect on the type of chips generated during orthogonal cutting (Rodkwan, 2002).

Currently, parawood makes up to seventy percents of raw materials used in Thai woodenm furniture industry (AsiaPulse News, 2003). Nevertheless, a few researches have been performed for the understanding of various furniture manufacturing processes such as machining and sanding using parawood. The use of Computer Numerical Control (CNC) wood router to machine parawood Laminated Veneer Lumber (LVL) and solid parawood using Cemented Tungsten Carbide tool was carried out (Ratnasingam and Perkins, 1998). In their work, it was found that the tool wear rate and power consumption are increased as cutting continues. Parawood LVL was also discovered to be four times more abrasive than solid parawood. The fundamental understanding of parawood sanding process was revealed (Ratnasingam *et al.,* 2002). It was found that sanding of parawood using Silicon Carbide abrasive belts was performed better than using Aluminum Oxide abrasive belt. The optimal cutting conditions of parawood machining using a Polycrystal Diamond (PCD) cutting tool ware were investigated (Prommul *et. al.*, 2002). In this work, spindle speed, feed rate and cutting direction are the major controlled parameters to study their effects on surface roughness and wood splinter. It was concluded that the condition which gives the best surface finish and no wood splinter was occurred at the spindle speed of 15,000 rpm and the feed rate of 8 m/min. The best surface quality of parawood were found at the spindle speed of 16,000 rpm and the feed rate of 12 m/min were used with Tungsten Carbide (TC) cutting tool (Arlai *et al.*, 2003).

The objective of this work is to investigate the effect of various machining parameters such as spindle speed, feed rate, depth of cut on product quality and tool wear through parawood machining process on a Computer Numerical Control (CNC) wood router. Additionally, optimal cutting conditions on parawood machining are determined using a statistical procedure.

## MATERIALS AND METHODS

The workpiece geometry is 39.4 in in length, 4 in in width and 1 in in board thickness. The mean specific gravity is 0.557 and the density at 12% m.c. is 620 Kg/m3. Tungsten Carbide tool grade T10MG with 3% Cobalt binder was used throughout the experiment as the cutting tool. The steps for determining the tool wear and surface quality investigation are described as follows: (1) identify the workpiece and measure the nose width of all tools using the optical microscope, (2) clamp the wood sample for the test on the CNC wood router table and set up spindle speed, feed rate and depth of cut following the experimental design shown in Table 1., then place the blade into the blade-holder for the first cut and next run for one pass to clean up the edge of workpiece, then stop the router, (3) replace the blade and place the tool into the blade-holder, (4) run the test for 1,000 linear feet and measure the nose width of each tool and take the pictures using microscope. Next, calculate arithmetic for the nose width, (5) repeat step (2) to step (4) again for the tool in 1,000 increments linear feet, stopping at 2,000, 3,000 linear feet to measure nose width and take

**Table 1** The cutting conditions used in this research.

| Spindle speed (rpm) | Feed rate (ipm) | Depth of cut (inch) | Designation's Code | Cutting distance (feet) | | |
|---|---|---|---|---|---|---|
| 12,000 | 180 | 0.0625 | PW1 | 1,000 | 2,000 | 3,000 |
| | | 0.1250 | PW2 | 1,000 | 2,000 | 3,000 |
| | 360 | 0.0625 | PW3 | 1,000 | 2,000 | 3,000 |
| | | 0.1250 | PW4 | 1,000 | 2,000 | 3,000 |
| 18,000 | 180 | 0.0625 | PW5 | 1,000 | 2,000 | 3,000 |
| | | 0.1250 | PW6 | 1,000 | 2,000 | 3,000 |
| | 360 | 0.0625 | PW7 | 1,000 | 2,000 | 3,000 |
| | | 0.1250 | PW8 | 1,000 | 2,000 | 3,000 |
| 15,000 | 180 | 0.0625 | PW9 | 1,000 | 2,000 | 3,000 |
| | | 0.1250 | PW10 | 1,000 | 2,000 | 3,000 |
| | 360 | 0.0625 | PW11 | 1,000 | 2,000 | 3,000 |
| | | 0.1250 | PW12 | 1,000 | 2,000 | 3,000 |

photograph and measure surface roughness of workpiece after 3,000 linear feet of machining by using profilometer**,** (6) after three replications, calculate the average of surface roughness of workpiece and nose width of test blades. Consequently, relationship among cutting distance, surface roughness, and nose width with various machining conditions was found designation code using a statistical program (Minitab14®).

## RESULTS AND DISCUSSIONS

The results from all cutting conditions described in Table 1 are shown in Table 2. In this study, blade wear was obtained by measuring nose width (NW) along various locations on the cutting edge. Figure 1 displays the measured nose width with different cutting distances on the blade; 1,000, 2,000 and 3,000 feet, respectively. Then, an image analysis software, image J®, was used to measure the nose width. It can be seen that the nose width becomes larger when the cutting distance is increased.

Consequently, all data in Table 2 were analyzed with statistical software, Minitab, to obtain the optimal condition of parawood machining process. The input parameters are spindle speeds at 12,000, 15,000 and 18,000 rpm, feed rates at 180, 360 ipm and depths of cut at 0.0625 and 0.1250 in, and the output parameters are surface quality and nose width. The testing hypotheses for the equality of treatment effects can be shown as follows:

$$H_0: \tau_1 = \tau_2 = \ldots = \tau_a = 0$$

$$H_1: \tau_i \neq 0 \text{ for at least one i}$$

The significance level to be used in this work is 0.05. Analysis of variance table of nose width and surface roughness in this research were also presented in Tables 3 and 4, respectively.

The result of analysis of variance when considering P-Value was found that spindle speed, feed rate, depth of cut, cutting distance, the spindle speed - feed rate interaction, the spindle speed - depth of cut interaction, the spindle speed - cutting distance interaction, the depth of cut – cutting distance interaction, the spindle speed - feed rate

**Table 2** Results from the machining tests.

| PW* | Variables | | | Nose Width (μin) | | | | Roughness** (μin) | Machining time*** (hr:min) |
|---|---|---|---|---|---|---|---|---|---|
| | Spindle speed (rpm) | Feed rate (ipm) | Depth of cut (in) | Cutting distance (feet) | | | | | |
| | | | | 0 | 1,000 | 2,000 | 3,000 | | |
| 1 | 12,000 | 180 | 0.0625 | 114.75 | 230.49 | 301.13 | 359.86 | 111.25 | 4:47 |
| 2 | 12,000 | 180 | 0.1250 | 132.54 | 215.58 | 278.75 | 306.83 | 142.29 | 4:56 |
| 3 | 12,000 | 360 | 0.0625 | 128.58 | 222.59 | 336.64 | 399.22 | 175.78 | 2:55 |
| 4 | 12,000 | 360 | 0.1250 | 142.57 | 242.34 | 280.75 | 344.97 | 142.30 | 2:56 |
| 5 | 18,000 | 180 | 0.0625 | 116.34 | 269.06 | 365.78 | 441.70 | 132.04 | 4:30 |
| 6 | 18,000 | 180 | 0.1250 | 140.83 | 225.41 | 271.97 | 341.14 | 207.70 | 4:24 |
| 7 | 18,000 | 360 | 0.0625 | 119.40 | 256.83 | 300.95 | 359.61 | 119.00 | 2:40 |
| 8 | 18.000 | 360 | 0.1250 | 145.22 | 224.80 | 258.40 | 296.98 | 171.76 | 2:40 |
| 9 | 15,000 | 180 | 0.0625 | 125.53 | 201.35 | 237.06 | 276.30 | 149.54 | 4:27 |
| 10 | 15,000 | 180 | 0.1250 | 137.32 | 201.68 | 278.78 | 322.63 | 125.34 | 4:28 |
| 11 | 15,000 | 360 | 0.0625 | 93.62 | 168.89 | 237.69 | 296.65 | 132.56 | 2:43 |
| 12 | 15,000 | 360 | 0.1250 | 121.59 | 183.48 | 243.56 | 315.20 | 189.04 | 2:44 |

* Parawood

** Surface roughness of parawood material at 3,000 feet

*** Machining time after running the machine for 3,000 feet

- depth of cut interaction, the spindle speed – feed rate - cutting distance interaction, the spindle speed - depth of cut – cutting distance interaction and the spindle speed - feed rate - depth of cut - cutting distance interaction have P-Value less than 0.05. As a result, the main effect and interaction above significantly affect the nose width.

The main effect of spindle speed, feed rate, depth of cut and cutting distance are plotted in Figure 2. Spindle speed effect is 15,000 rpm,

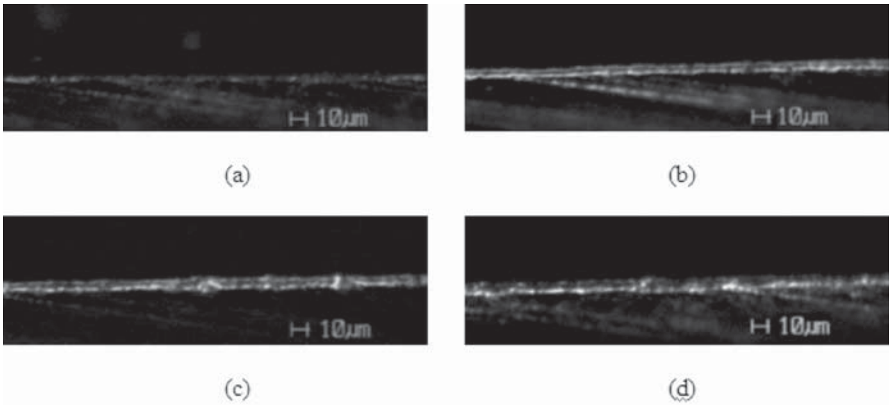


**Figure 1** Nose width of a tool at a spindle speed 18,000 rpm, a feed rate 360 ipm and a depth of cut of 0.0625 in (a) nose width of a new tool (b) nose width of a tool at 1,000 linear feet (c) nose width of a tool at 2,000 linear feet and (d) nose width of a tool at 3,000 linear feet.

**Table 3** Analysis of variance for nose width, with 95% of confidence.

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Blocks | 2 | 286 | 143 | 0.75 | 0.476 |
| Spindle speed (rpm) | 2 | 52060 | 26030 | 136.19 | 0.000 |
| Feed rate (ipm) | 1 | 1942 | 1942 | 10.16 | 0.002 |
| Depth of cut (in) | 1 | 6175 | 6175 | 32.31 | 0.000 |
| Cutting distance (ft) | 3 | 895716 | 298572 | 1562.1 | 0.000 |
| Spindle speed*Feed rate | 2 | 14133 | 7067 | 36.97 | 0.000 |
| Spindle speed*Depth of cut | 2 | 24019 | 12009 | 62.83 | 0.000 |
| Spindle speed*Cutting distance | 6 | 11066 | 1844 | 9.65 | 0.000 |
| Feed rate*Depth of cut | 1 | 233 | 233 | 1.22 | 0.272 |
| Feed rate*Cutting distance | 3 | 379 | 126 | 0.66 | 0.578 |
| Depth of cut* Cutting distance | 3 | 15539 | 5180 | 27.10 | 0.000 |
| Spindle speed* Feed rate*Depth of cut | 2 | 1750 | 875 | 4.58 | 0.013 |
| Spindle peed*Feed rate*Cutting distance | 6 | 11143 | 1857 | 9.72 | 0.000 |
| Spindle speed*Depth of cut*Cutting distance | 6 | 14337 | 2390 | 12.50 | 0.000 |
| Feed rate*Depth of cut* Cutting distance | 3 | 854 | 285 | 1.49 | 0.223 |
| Spindle speed*Feed rate*Depth of cut * Cutting distance | 6 | 4003 | 667 | 3.49 | 0.004 |
| Error | 94 | 17967 | 191 | | |
| Total | 143 | 1071601 | | | |

S = 13.8253 R-Sq = 98.32% R-Sq (adj) = 97.45%

**Table 4** Analysis of variance for surface roughness, with 95% of confidence.

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Blocks | 2 | 0.0000000 | 0.0000000 | 0.63 | 0.543 |
| Spindle speed (rpm) | 2 | 0.0000000 | 0.0000000 | 0.75 | 0.482 |
| Feed rate (ipm) | 1 | 0.0000000 | 0.0000000 | 3.04 | 0.095 |
| Depth of cut (in) | 1 | 0.0000000 | 0.0000000 | 3.07 | 0.093 |
| Spindle speed*Feed rate | 2 | 0.0000000 | 0.0000000 | 3.14 | 0.063 |
| Spindle speed*Depth of cut | 2 | 0.0000000 | 0.0000000 | 0.42 | 0.661 |
| Feed rate*Depth of cut | 1 | 0.0000000 | 0.0000000 | 0.13 | 0.722 |
| Spindle speed*Feed rate*Depth of cut | 2 | 0.0000000 | 0.0000000 | 6.66 | 0.005 |
| Error | 22 | 0.0000000 | 0.0000000 | | |
| Total | 35 | | | | |

S = 0.0000159618 R-Sq = 57.24% R-Sq (adj) = 31.98%

feed rate effect indicate mind inequality of nose width, with the treatment combination of 180 ipm possibly having larger nose width than 360 ipm, depth of cut effect reveals fairly of nose width, with the treatment combination of 0.0625 in possibly having larger nose width that 0.1250 in and if considered only main effect, they would run three factors at spindle speed 15,000 rpm, feed rate at 360 ipm and depth of cut 0.1250 in to minimize nose width form blade test. However, they are always necessary to examine any interactions that are important because the main effect do not have much meaning when the interaction significant affect.

The spindle speed - feed rate - depth of cut - cutting distance interaction is plotted in Figure 3. From the spindle speed - feed rate interaction, the optimal results obtain with a spindle speed of 15,000 rpm and a feed rate of 360 ipm. The spindle speed - depth of cut interaction indicates that depth of cut has smaller effect at 0.0625 in. The spindle speed - cutting distance interaction performs that spindle speed has smaller effect at 15,000 rpm. Therefore, the smaller nose width would appear to be obtained when a spindle speed at 15,000 rpm, feed rate at 360 ipm and depth of cut at 0.0625 in.

The result of analysis of variance when considering P-Value shows that the spindle speed

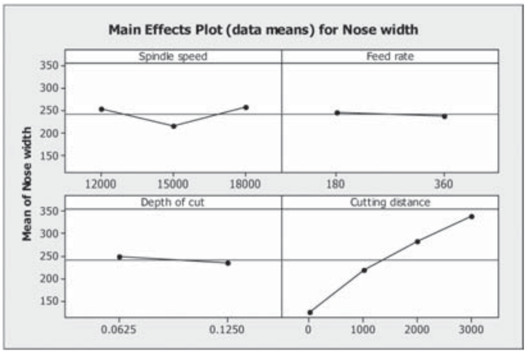


**Figure 2** Plot of main effect of nose width.

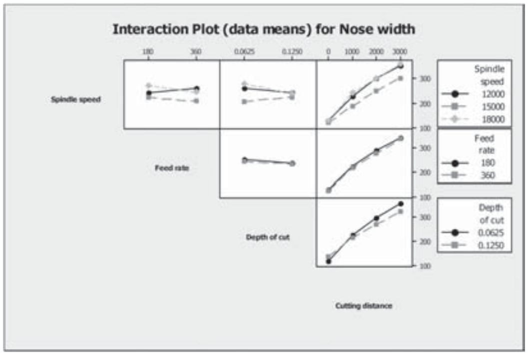


**Figure 3** The interaction plot (data means) for nose width (microinch).

– feed rate - depth of cut interaction have P-Value less than 0.05. As a result, that the interaction between spindle speed feed rate and depth of cut significantly affect the surface roughness of parawood material at 3,000 linear feet with 95% of confidence.

The spindle speed - feed rate - depth of cut interaction is plotted in Figure 4. The spindle speed - feed rate interaction reveal that the spindle speed and feed rate effect smaller surface roughness when spindle speed is at 12,000 rpm and feed rate is at 180 ipm. The spindle speed - feed rate - depth of cut interaction indicates that depth of cut has small effect at 0.0625 in with feed speed at 180 ipm, therefore, the smaller surface roughness would appear to be obtained when a spindle speed at 12,000 rpm, feed speed at 180 ipm and depth of cut 0.0625 in.

From this research, It was found that the optimal cutting conditions for the range of machining parameters studied considering the conditions with the least cutting tool wear and the least splinter were at the spindle speed of 15,000 rpm, the feed rate of 360 ipm and the depth of cut of 0.0625 in. Additionally, it was discovered that the cutting conditions to minimize the surface roughness of machined parawood include the spindle speed of 12,000 rpm, the feed rate of 180 ipm and the depth of cut of 0.0625 in.

In order to obtain the prediction model of optimization, a regression analysis on nose width versus spindle speed, feed rate, depth of cut, cutting distance; as a result, Equation 1 was presented.

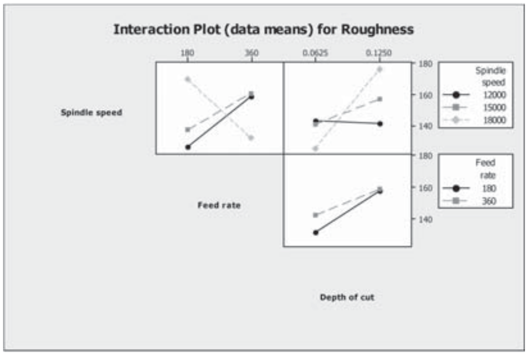


**Figure 4** The interaction plot (data means) for roughness (microinch).

Nose Width (μinch) = - 95 + 0.0156 spindle speed, rpm + 0.608 feed rate, ipm + 615 depth of cut, in + 0.0615 cutting distance, feet - 0.000046 spindle speed × feed rate - 0.0393 spindle speed × depth of cut + 0.000003 spindle speed × cutting distance + 0.068 depth of cut × cutting distance + 0.000048 spindle speed × feed rate × depth of cut - 0.000022 spindle speed × depth of cut × cutting distance (1)

Due to restriction of experiment setup and time, the statistical analysis using regression model was shown that the coefficient of determination of regression was very low that mean the data of surface roughness is not sufficient to analyze the regression model.

To test of a regression model, with a given spindle speed of 12,000 rpm, a feed rate of 360 ipm, and a depth of cut of 0.1250 in on a cutting distance at 3,000 feet, It is shown that the nose width of the blade is 373.895 μin. Compared with the empirical data in Table 2, it can be seen that the nose width of the tool with the same condition is 344.97 μin, closing this data; it can prove that the regression model can predict the nose width with 91.62% accuracy. Consequently, the regression model obtained in this work can be possibly used to predict the nose width of the tool in parawood machining process.

## CONCLUSIONS

In this study, the effect of various machining parameters such as spindle speed, feed rate and depth of cut in the parawood machining process were investigated on the quality of parawood machined surface and the wear of the Tungsten Carbide (TC) cutting tool. The ranges of machining parameters studied in this research are spindle speeds of 12,000, 15,000 and 18,000 rpm, feed rates of 180 and 360 ipm and depths of cut of 0.0625 and 0.1250 in. Using the statistical tool, the results show that the optimal cutting conditions for the range of machining parameters studied considering the conditions with the least cutting tool wear and the least splinter were found at the spindle speed of 15,000 rpm, the feed rate of 360 ipm and the depth of cut of 0.0625 in. In addition, it was concluded that the cutting conditions to minimize the surface roughness of machined parawood include the spindle speed of 12,000 rpm, the feed rate of 180 ipm and the depth of cut of 0.0625 in. The regression model was also obtained to predict the nose width and the surface roughness in each cutting condition. This study provides more understanding on parawood machining process in order to identify the optimal cutting condition where high quality machined surfaces with less surface roughness, less tooling cost, less waste materials, and lower production time are obtained. The selection of optimal machining parameters can be greatly contributed to engineers and operators in the parawood furniture manufacturing industry in Thailand and other countries in terms of productivity improvement, cutting parameter selection and produce component during machining process.

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