The Influence of Process Parameters on the Surface Roughness in Aesthetic Machining of Wooden Edge-Glued Panels (EGPs)

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This study explored the effect of processing parameters on surface roughness as a result of aesthetic designs processed on walnut, chestnut, and beech wood edge-glued panels (EGPs) by CNC (computer numerical control) router. To accomplish this, the average roughness value (R_a) on an engraved surface in a Ying-Yang design treated on the material was measured. Using analysis of variance (ANOVA), the feed rate, spindle speed, step-over, and axial depth of cut factors; surface roughness factors; and the interactions between these factors were found to form significant differences at the level of 95%. At the end of the study, the R_a value was lower in walnut and beech EGPs (3.423 μm and 4.316 μm, respectively) and higher in chestnut EGPs (5.005 μm).

Keywords: Surface roughness; Aesthetic machining; Wood edge-glued-panel (EGP); End-milling; Beech; Walnut; Chestnut

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INTRODUCTION

As the furniture industry moves from mass production to customer-oriented production, the design and production of customized products needs to be fast, and the manufacturing lead time needs to be shortened. To respond to these needs and increase profitability under a global marketing environment, firms attach importance to new technologies such as computer-aided production (CAP), computer-aided design and manufacturing (CAD/CAM), and their direct relative, CNC machines, in the workshop. The art of engraving holds an important place in the furniture manufacturing industry and can be applied by hand by valuable craftsman; however, engravings today can be carried out in shorter times as a result of the facilities provided by CAD/CAM technologies. It is important to know the processing parameters of the relevant technologies for engravings to be produced at the desired quality and cost. This study explored the effect of different processing parameters on surface roughness in making engraved wood panels.

Wood is a natural polymeric material with a heterogeneous structure. However, surface irregularities on solid wood surfaces are normally not considered as they are in other materials, such as metals and plastics (Zhong *et al.* 2013). Sinn *et al.* (2009) reported that wood surface properties were the result of complex and time-dependent interactions between the material and machining. They supported this finding with an overall review of the characteristics of solid wood surfaces and characterization techniques. With regard to the processing of the wood, there are numerous important factors, such as wood species, anatomical characteristics, moisture content, grain direction, feed rate, spindle speed, cutting depth, and tool geometry (Kopac and Sali 2003). Further improvements in technology, the development of different variants of engineered wood materials, different technological machinery, and different tools have made it necessary to continuously investigate the processing parameters.

When wood species were evaluated in terms of processing properties, hardwood was found to have better processing performance than softwood (Malkoçoğlu and Özdemir 2006). Because the density of latewood is higher, it has a lower surface roughness value than earlywood (Malkoçoğlu 2007).

Iskra and Tanaka (2005) reported that surface roughness had a direct relation to the inclination angle of wood grain and feed rate. Mitchell and Lemaster (2002) reported that processing at grain surfaces and on the flat side relative to the grain provide better surface quality than processing perpendicular, curve, and transversal faces; it was also pointed out that the surface quality in perpendicular, curve, and transversal cut surfaces decreases with increasing feed rate. The surface formation mechanisms that occur when processing with a straight blade and up- and down-milling at various grain angles have been studied. The forces occurring in the cutting process have been reconsidered for application to wood (Goli *et al.* 2004).

Wooden EGPs are increasingly gaining importance as an alternative substitute to other wood-based products in the furniture manufacturing process. Currently, many furniture firms use EGPs in products such as tables, beds or chests, and doors (Mitchell *et al.* 2005). The total production capacity of EGPs in Europe is reported to be approximately 2 to 2.5 million m^3/year (Dilik *et al.* 2012).

Wood EGPs are simply created from narrow strips of lumber that are glued together under pressure. Some of the advantages of edge-glued panel production are the relatively low cost of equipment, the smaller diameter and low-value grades of lumber, flexibility in panel product sizes, and opportunities to sell products within established local markets (Nicholls 2010).

Until recently, there were a limited number of studies of the processing of wooden EGPs and the aesthetic machining of wood separately. With regard to the aesthetic machining of wood materials, Negata *et al.* (2007) studied a robotic sanding system for attractively designed furniture with free-formed surfaces. Nagata *et al.* (2009) introduced an intelligent machining system based on a three-axis NC machine tool with a rotary unit for producing many kinds of specially designed wooden paint rollers. Also, Fujino *et al.* (2003) examined the influence of machining conditions such as feed rate and feed direction to the grain using two wood species. With respect to the machining of wooden EGPs, Sutcu (2013) reported that by making routing operations on pine, spruce, and beech EGPs both in the fiber direction and perpendicular to the fibers, the surface roughness with the relevant processing factors were found to be 34% for pine EGPs, 49% for spruce EGPs, and 27% for beech EGPs, respectively. Furthermore, the cutting direction is important for pine EGPs, the cutting depth and feed rate are important for spruce EGPs, and the cutting direction and feed rate are important for beech EGPs. Thus, the issue of aesthetic processing should be investigated further. The aim of this study was to determine how effective some processing parameters (*e.g.* feed rate, spindle speed, axial depth of cut, and step-over) are on the average roughness value (R_a), an important indicator of product quality, during the course of aesthetic processing of walnut, beech, and chestnut EGPs with a CNC router, to determine the level of effectiveness of the factors and interactions among them.

EXPERIMENTAL

Testing Material

A/B-class walnut, chestnut, and beech EGPs with 18-mm thicknesses were used (see Dilik *et al.* 2012 for the quality classes and standardization).

It is well known that walnut is a tight-grained and dense hardwood. Because of its interesting grain pattern, black walnut is of significant value for furniture, architectural woodwork, flooring, and decorative panels. Other important uses are gunstocks, cabinets, and interior woodwork (Miller 1999; Zhong *et al.* 2013). Beech is a dense, pale-colored hardwood. It has a fine structure with tight and large rays. Although beech wood is a hard and strong material, it does not have the endurance level of some other hardwoods (Zhong *et al.* 2013). Most beech is used for furniture, flooring material, brush blocks, handles, veneers, woodenware, and containers (Miller 1999). Chestnut wood is coarse in texture; annual rings are made conspicuous by several rows of large, distinct pores at the beginning of each year's growth, and it has rich tannin content. It dries well and is easy to work with tools (Miller 1999). Because of its tannin content, it has a natural resistance to fungi, insects, and parasites. It can easily be polished and demonstrates good adhesion, wear resistance, hardness, strength, dimensional stability, and screw retention (Ay and Şahin 2002). Additionally, chestnut is widely used in underwater construction, ship and boat construction, parquet, and flooring (Gorisek and Strase 2011).

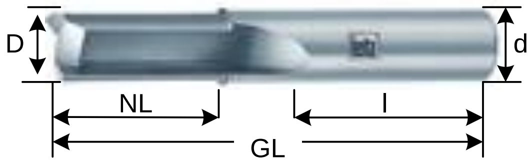
Before processing, the moisture contents of the wood panels were measured in accordance with TS 2471 (2005), and the densities of the wood panels were measured in accordance with TS 2472 (2005). The density and moisture contents for samples of wooden EGPs are summarized in Table 1.

Table 1. Values of Density and Moisture Contents for Samples of Wooden EGPs

Materials	Moisture Content (%)	Density (gr/ cm^3)
Beech EGPs	7.93	0.609
Chestnut EGPs	8.11	0.478
Walnut EGPs	7.22	0.627

Machining Treatments

Materials were processed with a modified Mekano P1500 model CNC router in our laboratory at the Suleyman Demirel University Faculty of Forestry. The table was fixed on the CNC router, and the spindle moved along the X, Y, and Z axes. The bench magazine capacity is limited to one set of coupling. The maximum spindle speed was set to 18,000 rpm. As a cutting tool, a 6-mm-diameter tungsten carbide-solid straight router bit with two blades was used (Fig. 1) (Leitz GmbH & Co. KG, 2012).



D: Diameter of the cutting edge : 6 mm
NL: Usable cutting length, : 14 mm
GL: Total length : 50 mm
D : Shank diameter : Ø 6 mm
L : Shank length : 30 mm
Rotation direction: RLL (right hand rotation)

Fig. 1. Router cutter used on experiments

The experimental design was established according to the full factorial experimental design method. The main factors in the design of the experiment were feed rate, step-over, axial depth of cut, and spindle speed. Step-over can be defined as the "radial depth of cut" in this study. By carrying out a full factorial design with these factors, 3x3x4x4 = 144 samples were processed for each type of EGP. Factors taken into account and their levels are shown in Table 2. The test sequence was determined completely at random.

Table 2. End-Milling Parameters

Factors	**Levels**			
Feed rate	0.25 m/min	0.5 m/min	0.75 m/min	1 m/min
Step-over	1 mm	2 mm	3 mm	4 mm
Axial depth of cut	2 mm	4 mm	6 mm	--
Spindle speed	12,000 rpm	15,000 rpm	18,000 rpm	--

The piece geometry and the cutting paths were defined by ArtCAM® (Artistic CAD/CAM) software. As an aesthetic design, a Ying-Yang model was processed, as it is a universal design and is preferred in freeform surface feature studies (Fig. 2) (see Sun *et al.* 2001).

After the design was created, the processing was carried out by transferring the CAM model to a computer connected to a CNC router (Fig. 3). The tool path used was a spiral tool path. The cutting tool path with the spiral tool processes the created model in an inward or outward circular motion. Sakarya and Goloğlu (2006) determined that a spiral tool path is the ideal tool path in finish processing for pocket milling.

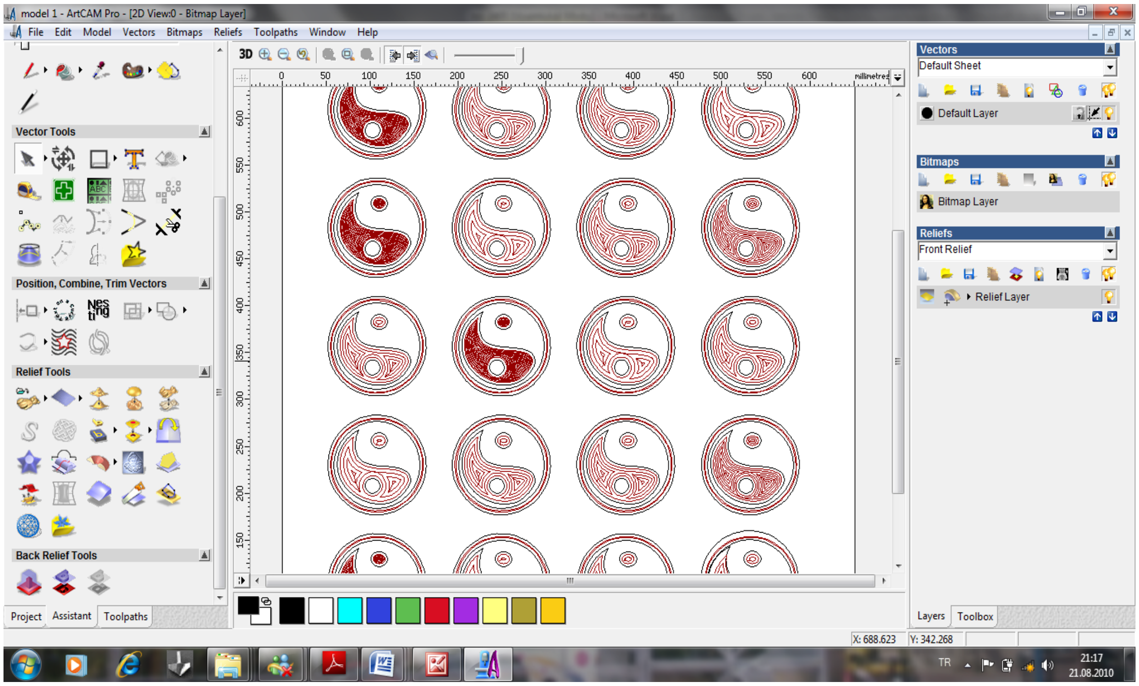


Fig. 2. Aesthetic Ying-Yang design prepared in ArtCAM


(a) (b)

Fig. 3. Operand (a) and processed (b) test samples

Surface Roughness Measurements

The first evaluations of surface roughness were made using visual observation and feel. This approach is very effective, but is also highly subjective. Currently, various sophisticated methods, such as the multi-element array diffuse reflection laser displacement sensor (CCD LDS) and camera-based vision systems (Sandak *et al.* 2004; Sinn *et al.* 2009), are available. The stylus technique is popular for evaluation of wood surface smoothness and is successfully employed due to its simplicity and its provision of accepted standard numerical values (Kilic *et al.* 2006; Zhong *et al*. 2013).

In this study, a Mitutoyo SJ 201 stylus-type surface roughness measuring device was used. This device operates on the inductive principle to measure the surface roughness. The instruments' measurement head fits a diamond tracer tip (5-µm radius), the measurement range is up to 350 µm, and the measuring force is 4 mN. The surface roughness parameter was measured over a traverse length of 5 mm and cut-off length of 0.8 mm using a Pc50 (Gaussian) filter. The traverse speed was set at 0.5 mm/s. The measuring parameter (R_a) is described in TS971 (1988) (adapted from ISO468-'82). R_a represents the average surface roughness, which is very useful in understanding the quality of wood surfaces (Khazaeian *et al*. 2004).

The device gave all the relevant parameter results automatically with a computer connection and the correct software standards.

Three different surfaces were formed on the machined material. As shown in the Ying-Yang symbol (see Fig. 3b), milling operations were applied on the downmill side during climb cutting, on the opposite side during conventional cutting, and on the burr surface end during milling. In this study, the burr surface was chosen for the location of measuring surface roughness on the Ying-Yang symbol. The surface profile was engraved and measured along and across the grain on the wood surface. Five measurements were taken from the engraved surface in each test specimen.

Statistical Evaluation

A full factorial experimental design (four factors) provided a complete trial in each replicate of the experiment, and the factors provided all possible combinations of the levels utilized (Montgomery and Runger 2003). These factors are as follows: Factors A, B, C, and D with 4 levels of factor A, 4 levels of factor B, 3 levels of factor C, and 3 levels of factor D; each replicate contains all ab, ac, ad, bc, bd, cd, abc, abd, acd, bcd, and abcd treatment combinations.

SPSS statistical software was utilized for the evaluation of the experimental results and the effect of dependent variables on surface roughness (R_a). The interactions between these factors were used for univariate analysis.

Prior to analysis, all of the measured data were tested for normality using the Kolmogorov–Smirnov normality test, and the requirement that the error variance of the dependent variable should be equal in groups was checked by the Levene test and approved (Levene test $p > 0.05$).

For the determination of different groups after the variance analysis (ANOVA), the Duncan test, frequently used in similar studies, was used. The results of the multiple comparison tests conducted at 5% significance level were expressed in the form of a letter. The difference between the groups with the same letter was statistically insignificant.

RESULTS AND DISCUSSION

The results of the univariate analysis (UNIANOVA) of the surface roughness measurements for the wood EGPs processed by different machining conditionings in the CNC router are displayed in Table 3. The three wood EGP interactions between factors of interest and all factors were significant (P <5%). There was a significant effect of the processing parameters on the R_a value (Table 3).

For this calculation, the change in the single and multiple parameter interactions' average roughness value (R_a) is proportional to the R^2 value. As shown in the ANOVA table, the effects of part of these changes, *e.g.*, walnut EGPs: 71.9%, beech EGPs: 62.2%, and chestnut EGPs: 88.4%, on the change in the value of average roughness can be explained by main effects and interactions (see Table 3).

The effect of progress parameters on homogeneous materials processes like metals can be explained by the higher R^2 values (see Kirby *et al.* 2004). However, there are numerous factors that affect the machining of wood, including wood density, wood porosity, moisture content, extractives, grain figure, kinematics of the cutting process, and machine conditions (Kopac and Sali 2003; Sin *et al*. 2009). It is difficult to provide higher R^2 values because of the difficulty of forming a model with consideration of all the interactions in the model.

The heterogeneous structure is increasing by virtue of how the wooden EGP structure of the solid material is processed, as well as tangential or radial irregular laths placed side by side or end to end in the same plate (Sütçü 2013).

Interactions and levels of individual factor effects can be elucidated easily by the partial eta-squared value. The partial eta-squared (η^2_p) describes the proportion of variability associated with an effect when the variability associated with all other effects identified in the analysis has been removed from consideration (Fig. 4). It is commonly used to report the effect size estimate for ANOVA. Then, one can easily calculate η^2_p from the ANOVA output using a statistical package like SPSS (Fritz *et al.* 2012). Cohen (1992) proposed a conversion table for η^2, where 0.0099 constitutes a small effect, 0.0588 is a medium effect, and 0.1379 is a large effect.

Table 3. The ANOVA Table for Walnut, Beech, and Chestnut EGPs with Respect to Average Roughness (*Ra*)

Source of Variance	**Walnut EGPs**						**Beech EGPs**						**Chestnut EGPs**					
	Sum of Squares	**df**	**Mean Square**	**F**	**Sig. (P)**	**P. Eta Squared**	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig. (P)**	**P. Eta Squared**	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig. (P)**	**P. Eta Squared**
Corrected Model	982.80 (a)	143	6.87	13.86	0.000	0.775	740.64(b)	143	5.18	9.26	0.000	0.697	5456.24(c)	143	38.16	39.20	0.000	0.907
Intercept	8435	1	8435	17.01	0.000	0.967	13389	1	13389	23930	0.000	0.977	18038	1	18.038	18528	0.000	0.970
Feed rate (A)	44.69	3	14.89	30.04	0.000	0.135	87.11	3	29.04	51.90	0.000	0.213	98.25	3	32.75	33.64	0.000	0.149
Step over (B)	8.65	3	2.88	5.82	0.001	0.029	68.17	3	22.72	40.61	0.000	0.175	293.37	3	97.79	100.45	0.000	0.343
Axial depth of cut (C)	33.77	2	16.88	34.05	0.000	0.106	3.98	2	1.99	3.556	0.029	0.012	403.30	2	201.65	207.14	0.000	0.418
Spindle speed (D)	3.59	2	1.79	3.62	0.027	0.012	23.46	2	11.73	20.96	0.000	0.068	38.43	2	19.21	19.74	0.000	0.064
Interaction (AB)	38.94	9	4.32	8.73	0.000	0.120	63.27	9	7.03	12.57	0.000	0.164	795.81	9	88.42	90.829	0.000	0.587
Interaction (AC)	105.32	6	17.55	35.40	0.000	0.269	8.29	6	1.38	2.47	0.023	0.025	122.98	6	20.49	21.05	0.000	0.180
Interaction (BC)	14.65	6	2.44	4.92	0.000	0.049	30.87	6	5.15	9.20	0.000	0.088	209.86	6	34.97	35.93	0.000	0.272
Interaction (ABC)	131.44	18	7.30	14.73	0.000	0.315	114.18	18	6.34	11.34	0.000	0.262	561.70	18	31.21	32.05	0.000	0.500
Interaction (AD)	41.94	6	6.99	14.10	0.000	0.128	48.26	6	8.04	14.38	0.000	0.130	460.95	6	76.82	78.91	0.000	0.451
Interaction (BD)	12.02	6	2.00	4.04	0.001	0.040	29.53	6	4.92	8.80	0.000	0.084	343.49	6	57.25	58.81	0.000	0.380
Interaction (ABD)	112.87	18	6.27	12.65	0.000	0.283	61.45	18	3.41	6.10	0.000	0.160	400.21	18	22.23	22.84	0.000	0.416
Interaction (CD)	34.92	4	8.73	17.61	0.000	0.109	14.96	4	3.74	6.69	0.000	0.044	173.01	4	43.25	44.43	0.000	0.236
Interaction (ACD)	107.46	12	8.96	18.06	0.000	0.273	24.86	12	2.07	3.70	0.000	0.072	219.56	12	18.29	18.79	0.000	0.281
Interaction (BCD)	80.33	12	6.69	13.50	0.000	0.220	45.64	12	3.80	6.80	0.000	0.124	431.70	12	35.97	36.95	0.000	0.435
Interaction (ABCD)	212.21	36	5.90	11.89	0.000	0.426	125.19	36	3.48	6.22	0.000	0.280	903.63	36	25.10	25.78	0.000	0.617
Error	285.61	576	0.50				321.72	575	0.56				560.75	576	0.97			
Total	9703.98	720					14428.32	719					24055.31	720				
Corrected Total	1268.41	719					1062.36	718					6016.99	719				
a. R Squared = 0.775 (Adjusted R Squared = 0.719)							b. R Squared =0.697 (Adjusted R Squared = 0.622)						c. R Squared =0.907 (Adjusted R Squared = 0.884)					

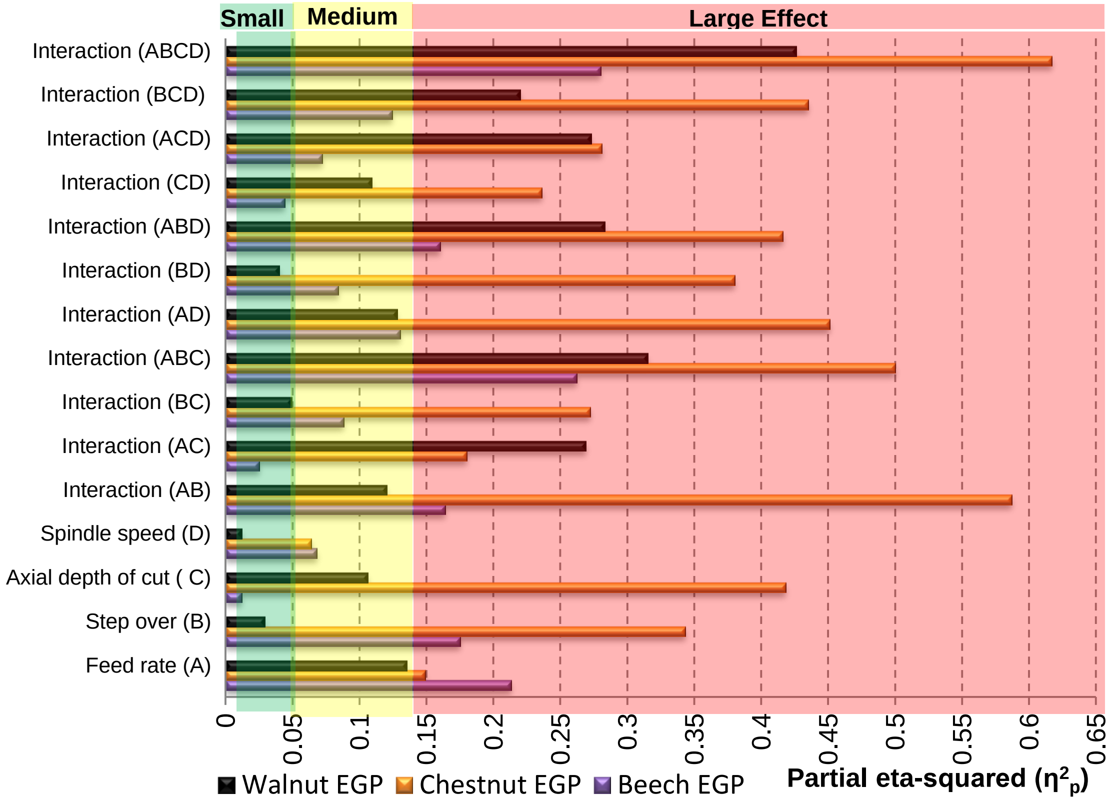


Fig. 4. Schematic illustration of the η^2_p statistic as a useful measure of the contribution of an effect — of a factor or an interaction — to the average roughness

The graph of the η^2_p statistic for main effects and interactions is shown in Fig. 4, in which it can be seen that the spindle speed factor was found to be less effective for the walnut EGPs and chestnut EGPs, but "axial depth of cut" was found to be effective for the beech EGPs.

Another important issue is the fact that the main or interaction factors, which depend on the wood species, show different levels of impact. The type of processing parameters are important for choosing the material to be machined, and wood processing parameters are an indication of the need to separately investigate each material. For instance, while "axial depth of cut" has a large effect on the R_a value for chestnut EGPs, there is a low effect for beech EGPs.

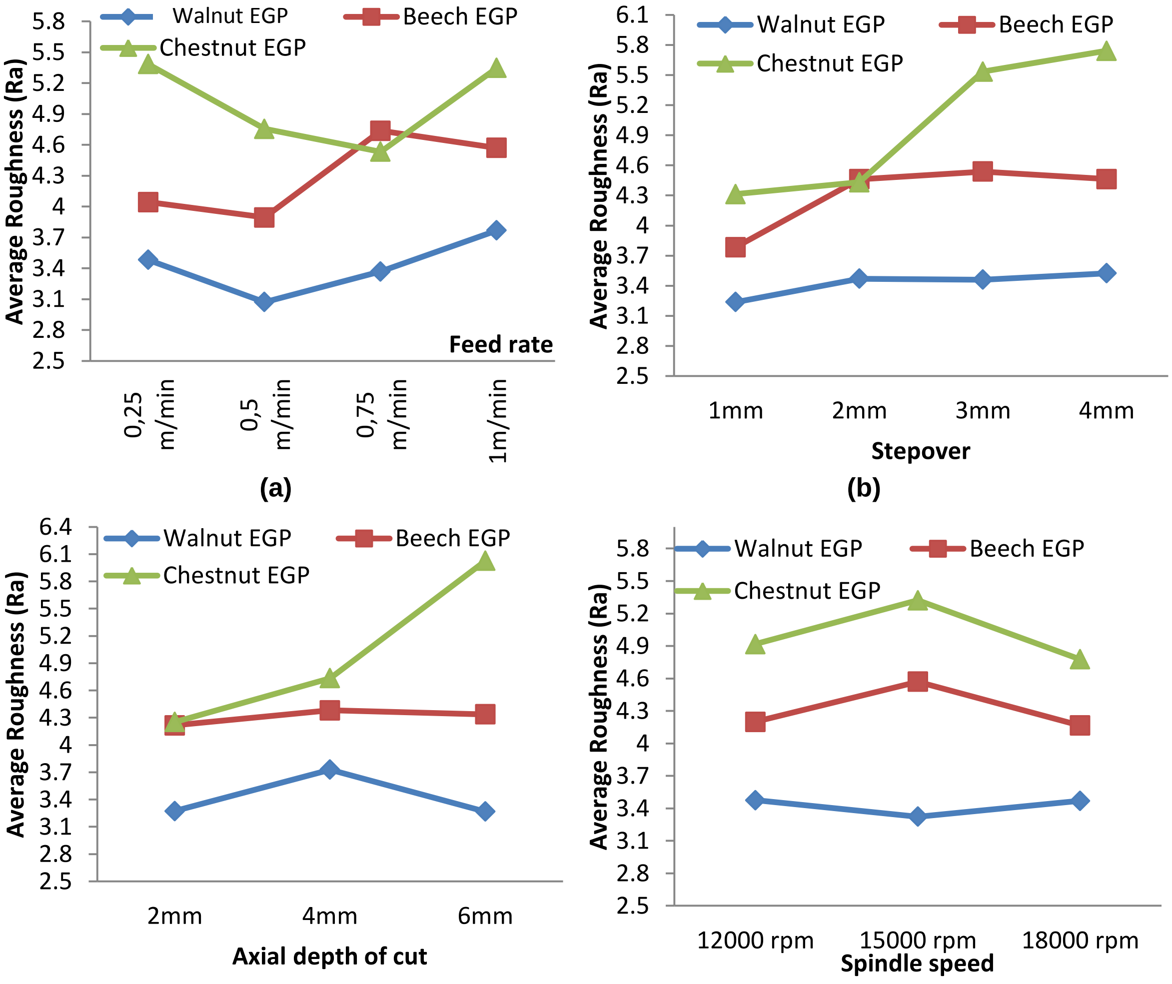
Although the "axial depth of cut" factor does not have a good effect on the average roughness, according to previous studies (Iskra and Tanaka 2005; Hernandez and Cool 2008; Sütçü 2013), a small effect for beech EGPs, a medium effect for walnut EGPs, and a large effect for chestnut EGPs were observed by employing a full factorial experiment and by processing 144 substrates for each EGP type.

Multiple comparisons to determine significant differences between groups (post-hoc technique) using the Duncan test were performed, and the results are summarized in homogeneous groups in Table 4.

Table 4. Homogeneous Subsets for Average Roughness

Factors	Levels	**Average Roughness** Means$^{(x)}$ µm		
		Walnut EGPs	Beech EGPs	Chestnut EGPs
Feed rate	0.25 m/min	3.483^{c}	4.043^{c}	5.385^{a}
	0.5 m/min	3.072^{b}	3.894^{c}	4.755^{c}
	0.75 m/min	3.369^{c}	4.737^{a}	4.534^{b}
	1m/min	3.768^{a}	4.571^{b}	5.348^{a}
Step-over	1mm	3.238^{d}	3.785^{e}	4.313^{f}
	2mm	3.470^{e}	4.461^{d}	4.432^{f}
	3mm	3.460^{e}	4.538^{d}	5.535^{e}
	4mm	3.524^{e}	4.463^{d}	5.742^{d}
Axial depth of cut	2mm	3.273^{f}	4.216^{f}	4.254^{i}
	4mm	3.729^{g}	4.381^{g}	4.735^{h}
	6mm	3.267^{f}	$4.337^{f,g}$	6.027^{g}
Spindle speed	12000 rpm	3.476^{i}	4.199^{h}	4.917^{k}
	15000 rpm	3.323^{h}	4.570^{i}	5.322^{j}
	18000 rpm	3.469^{i}	4.165^{h}	4.777^{k}

$^{(x)}$Means in the same column followed by different letters are significantly different at P<5% (Duncan's Multiple Range Test)



(a) (b) (c) (d)

Fig. 5. Effects of the processing parameters: (a) Feed speed, (b) Step-over, (c) Axial depth of cut, and (d) Spindle speed

Factor levels depended on the expected trend of continuous increase or decrease according to the results of this experiment, and therefore the results could not produce generalizations. As can be seen in Fig. 5, a positive correlation can be seen between "axial depth of cut" and "average roughness" with chestnut EGPs by observing the factor levels (Fig. 5c). Especially, the "higher spindle speed, lower average roughness," and "higher feed rate, higher average roughness" generalizations do not hold in the examined value range (Fig. 5a and 5d). Some researchers have explained that spindle speed does not have an effect on machining of some wood species and processing types (Mitchell and Lemaster 2002; Prommul *et al*. 2004; Farrokhpayam *et al.* 2010). In the present experiment, the existence of a significant effect with partial eta squared was demonstrated, but the shape of the effect could not be determined. The step-over factor, which is stated as the radial depth of cut, depends on straight or ball end mill, and is directly related to the diameter of the tools. This study was conducted using a straight end mill (Ø = 6 mm), and a low R_a value was obtained for beech and walnut EGPs for a 1-mm step-over; similar values are observed for 2-, 3-, and 4-mm step-overs (Table 4).

While there were no differences between 1- and 2-mm step-overs in chestnut EGPs, as the step-over ratio increased, the roughness value also increased significantly above 2 mm (Table 4 and Fig. 5b).

With regard to feed rate, the average roughness was in the range of 0.25 to 0.5 m/min for beech and walnut EGPs and 0.25 to 0.75 m/min for chestnut EGPs. The fact that R_a was high with low feed rate values can probably be related to chip formation. Su and Wang (2002), in their study on maple and fir solid wood, concluded that as feed rate increased between 0.6 and 3.6 m/min, the feed rate range for granular chips decreased and the flow-type chip rate increased, creating better surface quality. Considering beech and walnut EGPs at 0.5 m/min and chestnut EGPs above 0.75 m/min, R_a increased as the feed speed increased (Fig. 5a). This is probably related to the higher cutting forces occurring at higher feed speeds (Hernandez and Cool 2008).

The wood EGPs investigated have different behaviors toward processing parameters depending on the physical and anatomical characteristics of the wood species. In terms of all the factors, the best surface quality for the three hardwood EGPs was observed in walnut EGPs, which have the highest density (R_a = 3.423 µm; d = 0.627 g/cm^3), and the worst surface quality was observed in chestnut EGPs, which have the lowest density (R_a = 5.005 µm; d = 0.479 g/cm^3) (Fig. 5). A decrease in density resulted in an increase in porosity and thus increased the surface roughness as a result of the processing.

In general, wood species having high density may result in better machinability performance (Malkoçoğlu and Özdemir 2006). In addition, the porous formations of tree species are an important factor affecting the surface quality. Diffuse-porous wood has smoother surfaces than ring-porous wood (Malkoçoğlu, 2007). For this reason, it can be said that beech EGPs (Ra = 4.316 µm), the pore size of which becomes uniform within the annual ring (diffuse-porous), has a better surface than chestnut, whose earlywood pore size is bigger than that of its porous latewood (ring-porous). However, a better surface was obtained in semi-ring porous walnut EGPs than in chestnut EGPs (Fig. 5).

Non-homogeneity of wood is an important disadvantage in terms of machining. This heterogeneity is differently exhibited in different anatomical directions and cuts and is manifested in a high variability of wood properties. Annual rings provide an example of this. The annual rings typically consist of sequential layers with different density and porosity of wood tissue. When the motion of the tool is circular, the cutting edge alternately passes through these two different wood structures. This is expected to result in an increase in the amplitudes of vibrations of the tool and thus in high surface roughness (Kopac and Sali 2003).

The EGPs used in the experiments were created by sticking radial and tangential slats side by side to achieve dimensional stability from a technological point of view. This condition makes it necessary to evaluate both the radial and tangential sections at the same time. However, wood as un-isotropic material shows different properties in its three main directions – longitudinal, radial, and tangential. Thus, it is important to know along which direction the cutting is performed, as well as processing parameters. Many researchers have found that the tangential direction usually has higher surface quality than the radial direction (Örs and Gürleyen 2002; Kılıç *et al.* 2006; Buyuksari *et al.* 2011). These differences result in the excessive fluctuations in the measurements made by precise measurement tools, which leads to high variation among measurements (Fig. 6). For chestnut EGPs, in which porosity is high and density is low, the variability is at its maximum value (min: 1.69 µm; max: 13.07 µm).

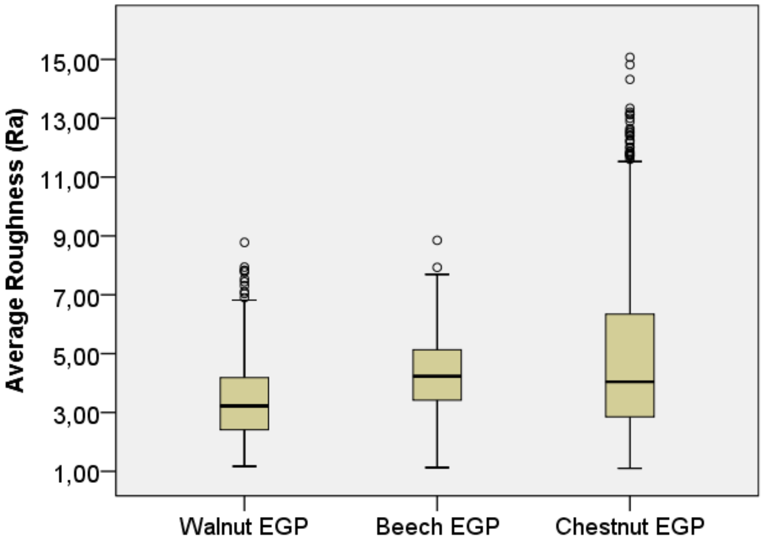


Fig. 6. Box and whisker plot of average roughness for aesthetic machining of walnut, beech, and chestnut EGPs

CONCLUSIONS

1. The extent of the single and multiple interactions of the processing parameters of interest responsible for the change in the average roughness were interpreted by statistical analyses. Accordingly, the change in average roughness, 71.9% for walnut EGPs, 62.2% for beech EGPs, and 88.4% for chestnut EGPs, and step-over, feed rate, axial depth of cut, and spindle speed, as well as their own, binary, triple and quadruple interactions, can be expressed. Therefore, to create higher prediction models in terms of validation, models covering interactions should be produced, in addition to models covering factors.

2. Factors for wood EGPs of interest, interactions between factors, and the processing factors with the least effect on average roughness were "spindle speed" for walnut EGPs and chestnut EGPs ($\eta^2{}_p$=0.012; $\eta^2{}_p$ =0.064) and "axial depth of cut" for beech EGPs.
3. In terms of feed rate, the best for walnut and beech EGPs is 0.5 m/min, and 0.75 m/min is best for chestnut EGPs. The average roughness increases with feed rates lower and higher than these values. The reason for this is probably the increase in granular chip rate and the increase in cutting force with high feed rates.
4. When evaluated in terms of step-over factor, meaning radial cutting depth, step-over rates lower than 1/6 Ø' for beech and walnut EGPs and 1/3 Ø for chestnut EGPs produced better surface quality.
5. When wood panels in which aesthetic processing was performed using a CNC router were evaluated in terms of tree species, walnut and beech EGPs were found to have smaller average roughness values (3.423 µm and 4.316 µm, respectively) than chestnut EGPs (5.005 µm).
6. The effect of the heterogeneity of wooden EGP on the surface roughness is inevitable. Anatomic structure, density, grain direction and cutting direction (radial or tangential section) are important factors. This can be expected to result in increases in the amplitudes of vibrations of the tool, and thus in high surface roughness. However, this heterogeneity leads to high variation among measurements.
7. In this study, a simple aesthetic processing was conducted using a 3-axis CNC and surface quality was evaluated by making measurements on the engraved surface of the processed material. For further studies, investigating the machining of free-form (sculptured) surfaces and 3D surface topography using a ball end mill is proposed.

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