Investigation of Parameters Affecting Surface Roughness in CNC Routing Operation on Wooden EGP

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The aim of this study was to evaluate the effect of CNC routing, using different parameters with the Taguchi experimental design, on the surface quality of various wooden (pine, spruce, and beech) edge-glued panels (EGP). The study evaluated five processing parameters: cutting direction, cutting depth, cutting width, feed rate, and spindle rotation speed, and their effects on surface roughness on pine, spruce, and beech EGP. Based on the results of statistical analysis of the burr surface roughness values, the mentioned parameters affected panels at varying levels. It was seen that the parameters were only responsible for ~34% (R_z) of the roughness on the surface of pine EGP, ~49% (R_z) of spruce EGP, and ~27% (R_q) of beech EGP. Statistically important parameters were as follows: cutting direction for pine, cutting depth (tip diameter) and feed rate for spruce, and cutting direction and feed rate for beech.

Keywords: Surface roughness; Wooden edge-glued panels; Routing; Hardwood; Softwood

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INTRODUCTION

Manufacturers have started to use more advanced technology in the processing of wood, which has the advantage of reducing labor costs during the last two decades. Nowadays, even in small and medium-sized wood product manufacturing plants, there can be one or several CNC machines. Some manufacturers demand CNC machines because they are able to achieve a higher quality of surface finish. For these manufacturing systems, since the set-up can be very precise and reproducible, determining the optimum manufacturing conditions to get the highest quality is of great importance. Thus, research has been conducted on manufacturing wood materials, considering the manufacturing parameters and the resulting surface quality of conventional manufacturing machines (Aguilera and Martin 2001; Malkaçoğlu 2007). The manufacturing conditions that affect the surface quality of solid wood for straight, cross-section, and profiled surfaces have also been examined (Mitchell and Lemaster 2002; Salca *et al*. 2008).

Some researchers have concentrated on examining the manufacturing parameters of MDF, which is more homogenous than solid wood (Aguilera *et al.* 2000; Davim *et al.* 2009; Sütçü and Karagöz 2012). The relation between the sound pressure level and surface roughness in milling using CNC machines has been examined in manufacturing using beech wood (Iskra and Tanaka 2005).

Wood is an anisotropic and heterogeneous natural material; therefore, tree species, density, anatomical structure, moisture content, and cutting direction can affect machining the wood directly or indirectly (Kopac and Sali 2003). Sinn *et al*. (2009)

reported that wood surface characteristics are the results of time-dependent, complex interactions of raw material and machining. They contributed with an overall review dealing with properties of wood surfaces, characterization, and measurement.

However, edge-glued panels (EGP), in addition to having the properties of wood, have a more heterogeneous structure than solid wood because of the style of cutting solid laths, which come together to form panels.

Many furniture companies utilize EGP in products such as table tops, bed or chest panels, and doors (Mitchell *et al.* 2005). Despite extensive study of the literature, no direct studies of the surface roughness of EGP have been found. Most of the studies about EGP focus on the finger joint method, as well as the elasticity and resistance properties of the joint components and the glues used for this purpose (Jokerst 1981; River and Okkonen 1991; Özçifçi and Yapıcı 2008).

In this study, five basic cutting parameters (axial and radial depth of cut, feed rate, cutting direction, and spindle speed), on three different EGPs (beech, spruce, pine), with an experimental setup made by the Taguchi experimental design, were manufactured in a CNC router. On the machined surface, the average roughness (R_a), highest mean peak-to-valley height (R_z), and root mean square deviation (R_q) values were measured with a surface roughness measuring device, and the results were analyzed.

EXPERIMENTAL

Materials

The material used was EGP made of pine, spruce (softwoods), or beech (hard-wood) using the finger joint method. During the preparation of the panels and manufac-turing of the finger joints, laths were not expected to have the same properties (radial + radial, tangential + tangential, *etc.*). Through the Taguchi experimental design method, the experiment setup was designed, and panels were processed in a CNC vertical machining center. For this purpose a Hartford VMC-1020 CNC router was used. This machine is equipped with a 6000 rpm spindle. Up to 30000 rpm can be reached by using spindle speeders and a maximum spindle power of 11 kW. The experiments were carried out with 4, 5, and 6 mm diameter router cutters. The straight router bits, made of k10 carbide, had two cutting blades with 15° rake angle and 15° clearance angles (Konyali Cutting Tools & Grinding Industry Ltd., 2011).

For measurement of the surface roughness, a Mitutoyo SJ 201 model stylus type surface measuring device was used because of its high reliability and capability to provide the user with precise surface measurements. This device operates on the inductive principle to measure the surface roughness. The instruments' measurement head fits with a diamond tracer tip (5 µm radius), measurement range of 350 µm, and a measuring force of 4 mN. The surface roughness parameter was measured over a traverse length of 5 mm, and cutoff length of 0.8 mm using a Pc50 (Gaussian) filter. Traverse speed was set at 0.5 mm/s. The measuring parameters (R_a, R_z, and R_q) are described in TS971 (1988) (adapted from ISO468-'82). The device gave all the relevant parameters with intended standards thanks to a computer connection and software.

The experimental set-up was designed according to the Taguchi experimental design method. The piece geometry was defined by CAD software. The cutting paths were defined by CAM software and machined with a CNC router.

After machining of every panel (450 ×1100 × 18 mm), eight samples were cut from each panel and the moisture contents determined according to TS 2471 (2005). Density was determined according to TS 2472 (2005). Figure 1 illustrates the test sample and measurement areas. The moisture contents of the samples were as follows: for beech EGP 6.78%; for spruce EGP 6.77%; and for pine EGP 9.29%. Similarly, the densities of the samples were: for beech panel 0.61 g/cm^3; for spruce panel 0.47 g/cm^3; and for pine panel 0.53 g/cm^3.

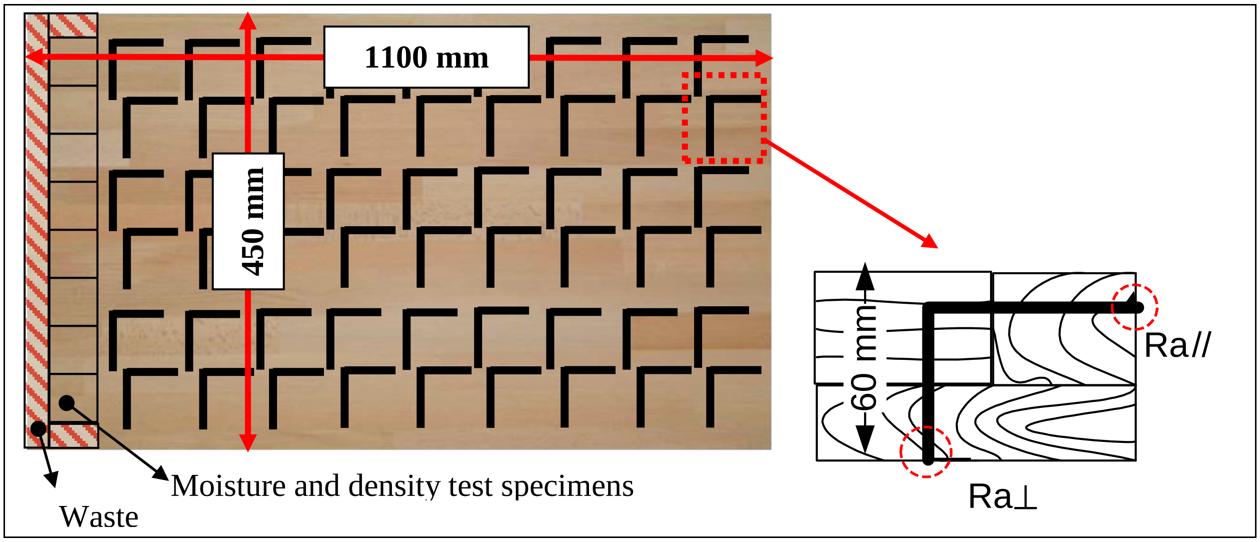

Fig. 1. A Sample and measurement areas

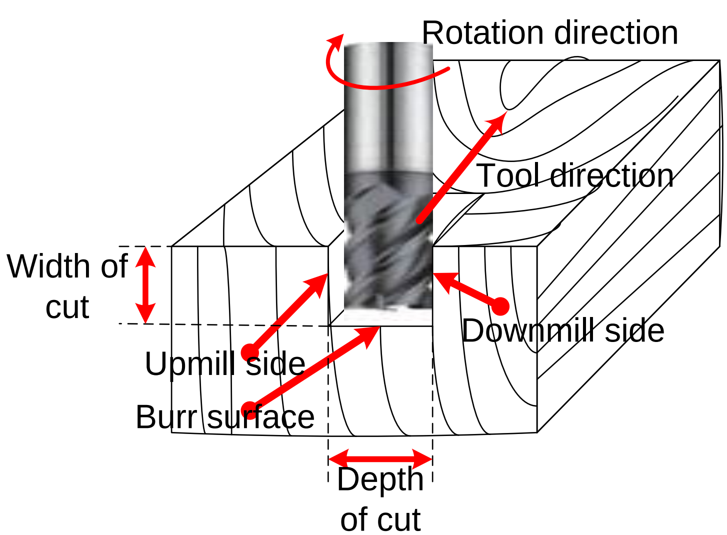

Fig. 2. Illustration of spindle and work piece for CNC router in buried cut

Three different surfaces were formed on the machined material. As shown in Fig. 2, on the downmill side climb cutting, on the opposite side conventional cutting, and on the burr surface end milling operating were applied. In this study, the surface roughness measurements were made on the burr surface.

Experimental Design

The Taguchi method is an experimental designing method that tries to minimize variability (of the product and process) and uncontrollable factors while designing experiments, and choosing the best configurations of the controllable factors with a reduced number of experiments compared to classical experimental layouts (Taguchi *et al.*, 2005).

Taguchi design is a set of methods considering main sources of variability of related responses at the design stage. Multiple factors can be studied at once in Taguchi designs (Zhang *et al*. 2007). In an experiment without a design, all combinations of factors are studied separately. A fractional factorial design in design of experiments is a reflection of a full factorial design. The main idea is to pull as much as information with fewer experiments instead of carrying out full combinations of experiments considering all of the factors affecting the related response. An orthogonal Taguchi design is also a factorial design developed by Genichi Taguchi.

In the literature, there are dozens of studies using the Taguchi experimental design method to obtain the optimum manufacturing conditions. Coelho *et al.* (2008) studied operations parameters for a better understanding of the effects of the key operations of wood machining on the quality of a finished wood surface. Yang and Chen (2001) and Zhang *et al.* (2007) stated that knowing the cutting parameters that will give the best surface smoothness before starting manufacturing is of vital importance. At first, a trial and error method was used to determine these optimum parameters, but it was a time-consuming process. To use the method, first factors and the factor inputs must be determined. For this purpose, recent scientific studies on face milling wooden materials and surface roughness were examined. Evaluated factors and factor inputs are briefly summarized in Table 1. Table 2 describes the specific factors in this experiment.

Table 1. Evaluated Factors and Factor Levels in Wood Milling in the Literature

Machining Factors	Mitchell and Lemaster (2002)	Aguilera *et al.* (2000)	Iskra and Tanaka (2005)	Ohuchi and Murase (2006)
Spindle rotation speed (rpm)	12000-18000	1800-12000	18000	15000
Tool diameter (mm)	12.7	14	20	10
Number of flutes	2	1	1	1
Cutter rake angle	--	18°	20°	22°
Depth of cut (mm)	Constant	2 -14	22	5
Width of cut (mm)	Constant	5 - 30	1 - 2	--
Workpiece material	Soft maple	MDF	Japanese beech	MDF
Feed speed	2.54, 5.08, 7.62, 11.43, 15.24 m/min	0-12 m/min	1,2,…,12 m/min	0, 1 (feed per knife mm)
Cutting edge material	Tungsten carbide	Carbide	Tungsten carbide k10	K05-cemented carbide

According to Taguchi *et al.* (2005), "Taguchi parameter design is started with selecting the proper orthogonal array according to the numbers of controllable factors (parameters). There are many orthogonal arrays. $L_4(2^3)$, $L_8(2^7)$, $L_{12}(2^{11})$, $L_{16}(2^{15})$ or $L_{32}(2^{31})$ belong to two-level series; $L_9(3^4)$, $L_{27}(3^{13})$, or $L_{81}(3^{40})$ are three level series; and

$L_{18}(2 \times 3^7)$ or $L_{36}(2^3 \times 3^{13})$ are mixed level arrays. In the experiment there are five factors in total, four of which have three levels and one has two level. It is recommended

Table 2. Considered Machining Factor and Factor Inputs in Taguchi Experimental Design

FACTORS		LEVELS		
		1	2	3
A	Tool direction (2 level)	Parallel to the grain (//)	Perpendicular to the grain (┴)	--
B	Width of cut	4 mm	6 mm	8 mm
C	Depth of cut	4 mm	5 mm	6 mm
D	Feed speed	2 m/min	4 m/min	6 m/min
E	Spindle rotation speed	15.000 rpm	18.000 rpm	21.000 rpm

that one use arrays such as L_{12}, L_{18}, and L_{36} because the interactions are almost evenly distributed to other columns, and there is no worry that an interaction confounds to a specific column or columns, thus leading to confusion". Thus, the parameter L_{18} was chosen for the purpose of this study. The factors were assigned to the columns of L_{18}, as shown in Table 3.

Table 3. Basic Taguchi L_{18} (2^1X3^7) Orthogonal Array (adapted from Taguchi *et al*. 2005)

No	A	B	C	D	E	F	G	H
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

Instead of carrying out (3x3x3x3x2) 162 experiments, 18 experiments were carried out in an L_{18} orthogonal design. The most effective factors for every parameter were determined by doing 54 experiments in a random order with three repetitions. Surface roughness, obtained for every kind of wood specimen, was examined using parameters of R_a, R_q, and R_z, and analysis of variance (ANOVA) was applied.

The factors in Table 2 were determined as controllable factors. Annual ring width, percentage of latewood, sapwood-heartwood forming conditions, radial-tangent cutting conditions of the laths next to each other on plaques, and finding natural defects on material surface are important factors that are expensive and time-consuming to control, and are therefore categorized as uncontrollable (defect, noise) factors. Three repetitions were made for every treatment, in case of a change in the uncontrollable factors in plaques.

RESULTS AND DISCUSSION

Three responses, which are R_a, R_z, and R_q, were measured for three different EGPs. Each experiment was conducted three times for each factor-level combination in this study to obtain error terms with limited resources. The experimental layout and results are given in Table 4.

Table 4. Experimental Layout and Results

Wood Species	Experiment No.	Cutting Direction	Width of Cut (mm)	Depth of Cut (mm)	Feed Rate (m/min)	Spindle Speed (rpm)	R_a		R_z		R_q	
		A	B	C	D	E	Ẍ (µm)	s^2	Ẍ (µm)	s^2	Ẍ (µm)	s^2
Beech	1	//	4	4	2	15 000	6,50	9,65	69,3	1026,1	9,48	16,09
	2	//	4	5	4	18 000	4,20	1,94	47,7	55,07	6,09	2,24
	3	//	4	6	6	21 000	8,18	3,20	71,7	102,43	11,03	5,55
	4	//	6	4	2	18 000	6,15	0,41	52,3	31,26	8,26	0,75
	5	//	6	5	4	21 000	8,53	0,50	76,5	5,40	11,23	0,36
	6	//	6	6	6	15 000	3,40	3,47	50,2	96,37	5,68	3,59
	7	//	8	4	4	15 000	7,85	1,67	64,8	96,65	10,11	3,07
	8	//	8	5	6	18 000	6,53	1,75	63,1	29,51	8,96	2,18
	9	//	8	6	2	21 000	8,69	0,41	68,0	94,94	11,45	0,79
	10	⊥	4	4	6	21 000	5,31	4,37	53,0	492,73	8,12	12,91
	11	⊥	4	5	2	15 000	9,96	18,90	83,8	590,09	14,73	49,48
	12	⊥	4	6	4	18 000	14,50	81,90	102,0	1700,0	18,87	119,63
	13	⊥	6	4	4	21 000	9,26	1,12	74,6	34,62	11,95	1,90
	14	⊥	6	5	6	15 000	6,22	10,00	54,8	41,77	8,89	9,73
	15	⊥	6	6	2	18 000	9,41	19,90	76,5	1195,1	12,67	28,31
	16	⊥	8	4	6	18 000	5,92	7,14	59,7	1061,9	8,82	19,22
	17	⊥	8	5	2	21 000	11,40	12,00	89,2	422,21	14,73	16,58
	18	⊥	8	6	4	15 000	5,74	2,27	62,5	79,61	8,52	3,05

Table 4. Experimental Layout and Results (Continued)

Wood Species	Experiment No.	Cutting Direction	Width of Cut (mm)	Depth of Cut (mm)	Feed Rate (m/min)	Spindle Speed (rpm)	R_a		R_z		R_q	
		A	B	C	D	E	Ẍ (µm)	s^2	Ẍ (µm)	s^2	Ẍ (µm)	s^2
Pine	1	//	4	4	2	15 000	8,92	26,20	64,3	914,56	11,68	45,21
	2	//	4	5	4	18 000	5,78	0,42	43,1	17,85	7,62	0,64
	3	//	4	6	6	21 000	8,14	6,33	70,5	194,98	11,04	7,12
	4	//	6	4	2	18 000	6,95	8,52	53,5	401,07	9,18	14,01
	5	//	6	5	4	21 000	8,33	2,98	63,5	242,19	11,11	6,28
	6	//	6	6	6	15 000	8,73	1,13	69,5	48,11	11,35	1,87
	7	//	8	4	4	15 000	5,55	4,11	47,0	102,71	7,21	5,14
	8	//	8	5	6	18 000	9,99	1,20	87,8	108,67	13,35	1,37
	9	//	8	6	2	21 000	9,14	4,07	70,0	35,32	11,80	5,08
	10	⊥	4	4	6	21 000	7,84	1,17	82,7	451,73	10,50	4,82
	11	⊥	4	5	2	15 000	11,70	30,60	96,1	1284,9	15,29	53,31
	12	⊥	4	6	4	18 000	9,66	1,27	110,0	318,84	13,82	3,93
	13	⊥	6	4	4	21 000	8,39	1,06	72,2	192,30	11,08	2,82
	14	⊥	6	5	6	15 000	8,81	1,76	84,1	192,24	12,06	4,12
	15	⊥	6	6	2	18 000	8,12	0,09	58,8	143,97	10,38	0,70
	16	⊥	8	4	6	18 000	13,60	29,60	125,0	2576,0	18,36	50,31
	17	⊥	8	5	2	21 000	7,68	3,54	70,5	557,92	10,50	9,13
	18	⊥	8	6	4	15 000	13,10	15,40	118,0	1073,8	18,67	38,04
Spruce	1	//	4	4	2	15 000	5,76	0,43	55,30	24,85	7,68	0,60
	2	//	4	5	4	18 000	4,47	0,58	35,00	22,56	5,88	1,13
	3	//	4	6	6	21 000	10,60	9,56	87,40	402,76	14,04	19,58
	4	//	6	4	2	18 000	4,21	0,40	47,70	74,20	5,98	0,60
	5	//	6	5	4	21 000	8,16	6,65	59,00	67,01	10,18	6,10
	6	//	6	6	6	15 000	6,60	0,93	55,30	57,57	8,69	0,94
	7	//	8	4	4	15 000	7,54	8,37	85,20	1864,8	10,97	28,28
	8	//	8	5	6	18 000	4,66	0,47	40,70	12,62	6,09	0,43
	9	//	8	6	2	21 000	8,76	1,25	76,50	615,06	11,73	5,34
	10	⊥	4	4	6	21 000	3,79	2,95	31,60	184,63	4,90	4,60
	11	⊥	4	5	2	15 000	5,19	0,54	56,60	139,15	7,38	0,25
	12	⊥	4	6	4	18 000	11,10	18,90	95,60	1708,4	15,01	34,02
	13	⊥	6	4	4	21 000	4,42	3,86	32,30	126,91	5,57	5,11
	14	⊥	6	5	6	15 000	6,28	0,41	49,30	183,0	8,65	1,74
	15	⊥	6	6	2	18 000	12,30	11,50	102,0	550,45	16,71	21,38
	16	⊥	8	4	6	18 000	7,78	28,60	55,80	1184,0	10,41	49,38
	17	⊥	8	5	2	21 000	8,78	1,04	92,50	591,30	14,16	18,93
	18	⊥	8	6	4	15 000	5,08	4,12	41,90	221,28	6,77	7,31

According to the study results, effects of the factors examined were limited. From the panels studied, an analysis of variance for values of R_a, R_z, and R_q, was developed (Table 5).

Table 5. Importance of the Factor Interactions of Surface Roughness Values of EGP

		Pine EGP			Spruce EGP			Beech EGP		
	df	$P(R_a)$	$P(R_z)$	$P(R_q)$	$P(R_a)$	$P(R_z)$	$P(R_q)$	$P(R_a)$	$P(R_z)$	$P(R_q)$
Cutting direction	1	0.049*	0.001*	0.030*	0.567	0.795	0.395	0.072	0.115	0.042*
Width of cut	2	0.370	0.135	0.300	0.954	0.622	0.780	0.771	0.664	0.614
Depth of cut	2	0.696	0.581	0.611	0.001*	0.008*	0.003*	0.517	0.460	0.491
Feed speed	2	0.659	0.181	0.665	0.000*	0.000*	0.000*	0.015*	0.029*	0.024*
Spindle rotation speed	2	0.577	0.613	0.558	0.325	0.276	0.343	0.593	0.537	0.604
S		3.521	28.464	4.778	2.784	24.424	3.959	3.908	23.595	4.882
R^2 (%)		16.67	33.79	19.30	46.48	48.53	46.43	26.12	24.07	26.56
R^2_{adj} (%)		0.00	20.25	2.79	35.53	38.00	35.47	11.01	8.54	11.54

* shows significance at 0.05

Table 5 shows the results of analysis of variance (ANOVA) that was done on the p-values. The coefficient of multiple determination R^2 can be used as a global statistic to assess the fit of the model. Many researchers prefer to use an adjusted R^2 statistic. These parameters are very useful in comparing and evaluating competing statistical models (Montgomery and Runger 2003). The degrees of freedom (df) and F values are used when comparing the test statistic to statistical tables, but that is not needed as we have a p-value given by software.

From the analysis, it is easy to identify which factors are significant in terms of surface quality parameters. As shown in Table 5, for pine EGP, only the cutting direction had a significant difference ($p < 0.05$), and a majority of the differences in surface roughness were a result of other factors, which are not to taken into consideration here ($R^2_{Ra} = 0.17$, $R^2_{Rz} = 0.34$, $R^2_{Rq} = 0.19$).

Hecker and Becker (1995), stated that the annual ring angle, wood density, and annual ring width are important parameters affecting the surface roughness. The fact that the examined machining parameters for pine produced no significant results supports this finding.

According to the results obtained for spruce EGP, the surface roughness of the material, among factors evaluated, is more effective than pine EGP and beech EGP (approximately 50%). Cutting depth and feed speed are the most significant factors. Nevertheless, it is possible to find resin ducts or large face knots at any moment on eye control of the samples machined because spruce panels have too many natural defects (Fig. 3a).

According to the results obtained for beech EGP, it can be said that the factors evaluated are effective on the surface roughness of the material by approximately 25%; cutting direction and feed speed are the most significant factors. However, it is well known that beech wood has a higher density and more homogenous anatomical features than the other wood samples (pine and spruce). As a result of these settings, better surface qualities were realized in this study (Fig. 3b). Moreover, Aguilera and Martin (2001) proposed that if the density is low, the roughness would be increased in terms of wood machining. Malkoçoğlu and Özdemir (2006) stated that hardwood allows a better machining than softwood, in terms of annual ring width and difference in wood density. The values found for beech EGP support these ideas.

In addition to these evaluations, it was seen that all machined species, especially in proximity of the panel's face, presented processing defects such as fuzzy or torn grain (Fig. 3c and 3d).

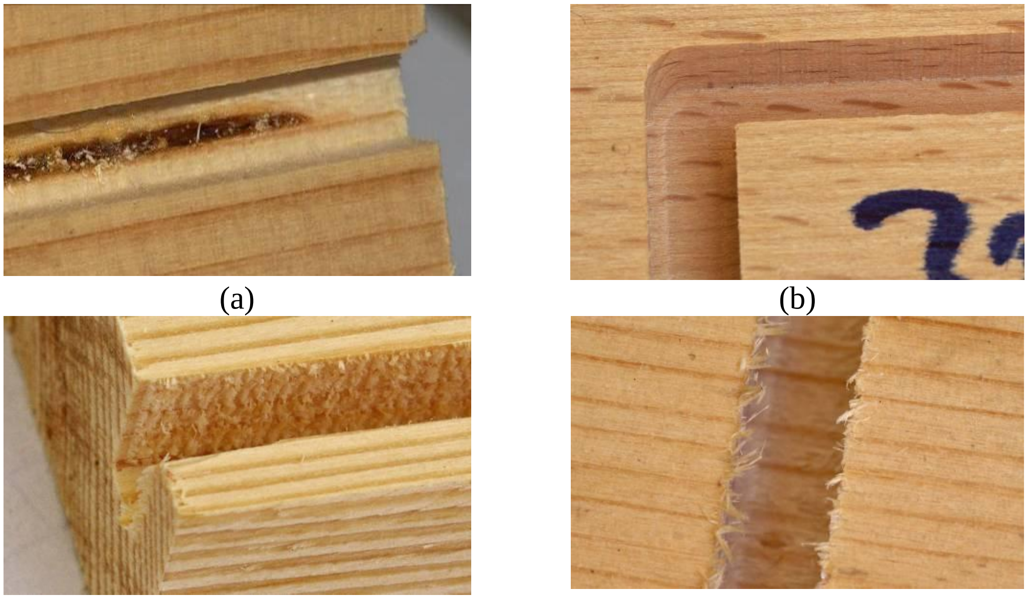

Fig. 3. Subjective perception of a finished surface. (a) resin ducts on spruce EGP, (b) Smooth surface on beech EGP, (c) torn grain on spruce EGP and (d) pine EGP

Regarding the side surfaces of the channels, up-milling occurred on one side and down-milling occurred on the other. This explains why torn fibers were only on one side. On the beech EGP sample, the effect of the up-milling and down-milling can be clearly seen (Fig. 4).

Fig. 4. Comparison of down-milling versus up-milling on the same channel on beech EGP

Mitchell and Lemaster (2002) stated that while machining solid maple wood, down-milling gives better results than up-milling on the flat grain surface. On end grain surfaces, up-milling gives better results. Increasing feed speed decreases the surface quality on every kind of surface. In the end of the study, as a general expression, tool direction is a significant factor in determining surface roughness for the flat side grain, but not for the curved side grain surfaces. The results obtained in this study were the same, except for the feed speed factor. No significant difference was seen for feed speed.

CONCLUSIONS

1. Five factors affecting machining wooden EGP were studied. However, as a result of statistical evaluations, it was found that the parameters were only responsible for ~34% (R_z) of the roughness on the surface of pine EGP, ~49% (R_z) of spruce EGP, and ~27% (R_q) of beech EGP (see Table 5). Especially on pine EGP and beech EGP, the fact that these values are so low shows the existence of more important factors affecting the surface roughness; these are not dealt with directly in this study.
2. The cutting direction of pine EGP in face milling, the cutting depth and spindle rotation speed for spruce EGP, and cutting direction and spindle rotation speed for beech EGP are important and effective factors. No significant effect can be seen of the axial depth of cut on any outcomes.
3. The influence of milling parameters on surface roughness in aesthetic machining of wooden panels should be studied in further research.

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