Determination of Optimal Machining Parameters of Massive Wooden Edge-Glued Panels Made of European larch (*Larix decidua* Mill.) using Taguchi Design Method

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In this paper, the optimization of computer numerical control (CNC) machining parameters were conducted using the Taguchi design method on the surface quality of massive wooden edge glued panels (EGP) made of European larch (*Larix decidua* Mill). Three machining parameters and their effects on surface roughness were evaluated. These parameters included tool clearance strategy, spindle speed, and feed rate. An analysis of variance (ANOVA) was performed to identify the significant factors affecting the surface roughness (R_a and R_z). Optimum machining parameter combinations were acquired by conducting an analysis of the signal-to-noise (*S/N*) ratio. Optimal cutting performance for the R_a and R_z was obtained for the cutter at a tool clearance strategy of an offset 16000 rpm spindle speed and 1000 mm/min feed rate. The surface roughness, both the R_a and R_z, increased with increasing feed rate. Optimal cutting performance for R_a and R_z was obtained for a tool clearance strategy of an offset 16000 rpm spindle speed, and 1000 mm/min feed rate cutting settings. Based on the confirmation tests, R_a decreased 2.2 times and R_z 1.8 times compared to the starting cutting parameters.

Keywords: Wood machining; European larch; Taguchi design method; Surface roughness

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INTRODUCTION

Wood and wood-based materials have been used as a construction material for years, mostly because of their low cost, renewability, strength, and low processing energy requirements. In recent years, the machining of wood products has acquired great importance because of the short supply of wood, as well as increasing environmental awareness among users and manufacturers. Consequently, the machining process is being optimized in terms of tool wear, work piece surface quality, crack initiation, and the utilization of different types of wood (Davim 2011).

The surface quality of solid wood and wood-based panels is one of the most important properties characterizing the wood-machining process and its conditions, as well as manufacturing processes, such as finishing or adhesive strength properties. The surface roughness of wood can be affected by different factors, such as annual ring variation, wood density, cell structure, earlywood ratio and latewood ratio, and humidity (Sandak and Tanaka 2003; Zhong *et al.* 2013). The stylus method is commonly used in laboratories and for off-line roughness measurements of wood and wood-based panel surfaces (Hiziroglu 1996; Hiziroglu and Graham 1998; Sandak and Tanaka 2003; Zhong *et al.* 2013).

European larch is one of the most important commercial species in Europe. Its wood is highly valued for lumber and particleboard (Muhcu *et al.* 2015). Wood edge-glued panels (EGP) have a more heterogeneous structure than solid wood (Sutcu 2013). Many furniture companies utilize EGP in products such as table tops, bed or chest panels, and doors (Mitchell and Lemaster 2002).

Computer numerical control (CNC) wood working machinery has been widely introduced in wood industries, especially in the furniture industry. Computer numerical control has been used for grooving, milling, and patterning of furniture materials. The use of CNC has good advantages with respect to the speed, surface quality, and precision machining of work pieces (Costes and Larricq 2002; Ohuchi and Murase 2005; Karagoz *et al.* 2011; Alves *et al.* 2015).

The Taguchi method (TM) combines engineering and statistical methods to attain rapid improvements in quality and cost by optimizing the product design and manufacturing processes. Taguchi method is a unique statistical experimental design approach that greatly improves the engineering productivity (Verma *et al.* 2012). The TM can be effectively used to determine the optimal combinations of machining process parameters. The number of experiments is reduced to minimize the cost and time using an orthogonal array (OA) (Valarmathi *et al.* 2013). The method explores the concept of quadratic quality loss function and uses a statistical measure of performance called Signal-to-Noise (*S/N*) ratio. The *S/N* ratio takes both the mean and the variability into account. The *S/N* ratio is the ratio of the mean (Signal) to the standard deviation (Noise). The ratio depends on the quality characteristics of the product/process that was optimized. The standard *S/N* ratios generally used are as follows: Nominal is Best (NB), Lower the Better (LB), and Higher the Better (HB). The optimal setting is depends on combination of the parameters, which has the highest *S/N* ratio (Patel and Patni 2014). In addition, an analysis of variance (ANOVA) determines the statistically significant process parameters. After the analyses (*S/N* and ANOVA) have been conducted, a confirmation experiment is performed to verify the optimal process parameters acquired from the parameter design (Taguchi *et al.* 1989; Nalbant *et al.* 2007; Gologlu and Sakarya 2008). Some researchers have reported on the effect of cutting speed and feed rate on surface roughness in wood and wood-based materials by milling and drilling of a CNC router (Davim *et al*. 2009; Sutcu and Karagoz 2012; Sutcu 2013; Valarmathi *et al* 2013). Benotmane and Zirouk (2013) studied the woodturning performance and efficiency by using the Taguchi methodology for dynamic systems. Wilkowski *et al*. (2011, 2013) used TM in order to investigate machinability and surface roughness of wood materials. Kacal and Gulesin (2011) studied determination of optimal cutting conditions in finish turning of austempered ductile iron using TM. Another study investigated optimization of the combined modification process of thermo-mechanical densification and heat treatment on Chinese fir wood (Li *et al*. 2013). Sofuoglu (2015) reported on using Artificial Neural Networks (ANN) to model the surface roughness of EGP made of Scotch pine in a machining process with CNC.

In this study, three important process variables (tool clearance strategy, spindle speed, and feed rate) with an experimental set up made by the Taguchi experimental design were investigated with a CNC router. Tool clearance strategy, which is area clearance strategy can be selected: raster or offset by CAM software (Fig. 2). On the machined surface, the average roughness (R_a) and highest mean peak to-valley height (R_z) values were measured with a surface roughness measuring device.

EXPERIMENTAL

In this study, the material used was 30-mm-thick EGP; the wood was from European larch (*Larix decidua* Mill.) trees. The EGP panels were supplied by ERPAN Massive Panel from Turkey. EGP panels were selected at random from the manufacturer.

During the preparation of the EGP panels and manufacturing of the finger joints, laths were not expected to have the same properties (radial + radial, tangential + tangential, knotless, *etc*). The density of the EGP was measured as 0.62 g/cm^3 at 12% moisture content ISO 3130 (1975); ISO 3131 (1975). The experiments were carried out on a Skilled CNC milling machine (Beysantaş A.Ş., Turkey) with a maximum spindle speed of 18000 rpm and a maximum feed rate of 2000 mm/min. The experiments were carried out with Netmak - 0450-07 (Ø10 x 30 x 72) (Netmak group, Turkey) and 10-mm-diameter router cutters made of a solid carbide. New and sharp cutters were used in each cutting test.

Three machining parameters (tool clearance strategy, spindle speed, and feed rate) were evaluated, as indicated in Table 1. A total of 18 pieces with dimensions of 50 x 50 mm were machined on EGP panels by a CNC router (Fig. 1). Depth of cuts were 4 mm (Fig. 2). Surface roughness was measured on every piece, in the radial direction, parallel to the grain, seven times. The measuring parameters (R_a and R_z) are described in ISO 468 (2009). ISO 468 defines R_a and R_z all measured relative to a straight mean line: R_a (centerline average) value is the arithmetic mean of the departures of a profile from the mean line. It is normally determined as the mean results of several consecutive sample lengths. R_z (ten-point height) is the average distance between the five height peaks and the five deepest valleys within the sampling length and measured perpendicular to it.

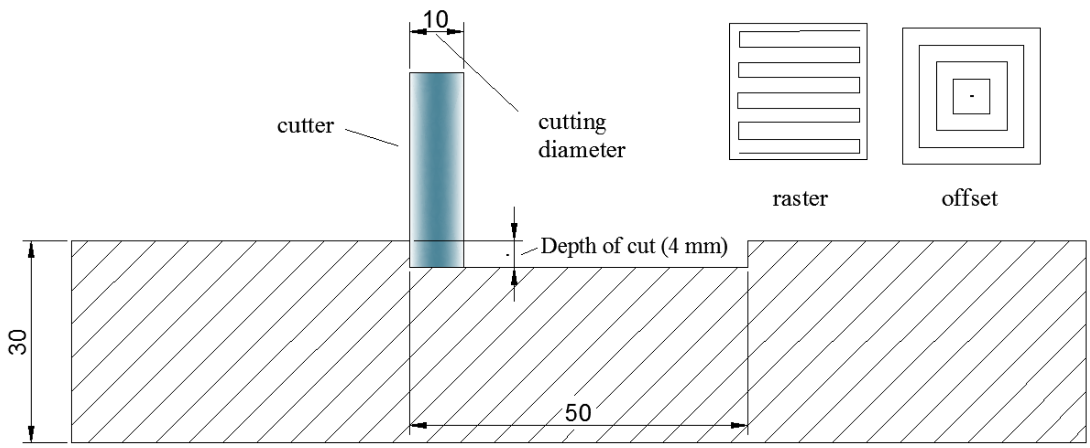


Fig. 2. Parameters of CNC process

Table 1. Assignment of Levels to Factors (Machining Parameters used in the Face Milling of EGP Made of European Larch)

Symbol	Machining parameter	Coded levels		
		Level 1	Level 2	Level 3
A	Tool clearance strategy	Raster	Offset	
B	Spindle speed (rpm)	8000	12000	16000
C	Feed rate (mm/min)	1000	1500	2000

The measurement of surface roughness was conducted according to the protocols in ISO 468 (2009), ISO 3274 (2005), and ISO 4287 (1997). The Surface Roughness Tester (TR200, TIME, China) surface roughness measurement device, which has a diamond stylus, was used. Measurements were taken along the grain. The sampling length was taken as 2.5 mm; the evaluation length was chosen as Lt= 12.5 mm. Surface roughness values were measured with a sensitivity of ± 0.01 µm. The tool measurement speed was chosen as 10 mm/min, the diameter of the measurement needle was 4 µm, and the needle tip orientation was 90°.

Wood machining parameters were used as control factors, where 1 parameter was designed to have 2 levels and 2 parameters were designed to have 3 levels (Table 1). In accordance with TM, a L_{18} OA table with 18 rows (corresponding to the number of experiments) was selected for the experiments.

Statistical analyses (*S/N*, ANOVA) were performed by using MINITAB R17 software for a confidence level of 95% (*e.g.*, significance level of 0.05).

To obtain an optimal cutting performance, the-smaller-the-better quality characteristics for R_a and R_z *S/N* ratio (η) are defined as,

$$\eta = -10\ log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \quad (1)$$

where y is the observed data and n is the number of observations.

RESULTS AND DISCUSSION

Average surface roughness (R_a) values were obtained as 1.89 µm and highest mean peak to-valley height (R_z) values were obtained as 8.30 µm. The measured data gives the normal distribution at the 95% confidence level. The experimental design of L_{18} and the experimental results and *S/N* ratios are given in Table 2. The optimal level of the process parameters is the level with the greatest η value. According to η value, main effects plots were prepared (Figs. 3b and 4b).

Table 2. Experimental Design using an L_{18} Orthogonal Array and the Results and *S/N* Ratio for R_a and R_z

Exp. no	A Tool Clearance Strategy	B Spindle Speed (rpm)	C Feed Rate (mm/min)	R_a		R_z	
				Measured (µm)	S/N (dB)	Measured (µm)	S/N (dB)
1	1	8000	1000	1.62	-4.20	8.42	-18.51
2	1	8000	1500	1.86	-5.40	8.07	-18.14
3	1	8000	2000	2.50	-7.95	10.8	-20.64
4	1	12000	1000	1.98	-5.95	8.52	-18.60
5	1	12000	1500	1.96	-5.83	8.40	-18.48
6	1	12000	2000	2.29	-7.21	10.07	-20.06
7	1	16000	1000	1.68	-4.52	7.83	-17.88
8	1	16000	1500	1.62	-4.20	7.27	-17.23
9	1	16000	2000	1.52	-3.63	7.09	-17.00
10	2	8000	1000	1.97	-5.90	8,39	-18.47
11	2	8000	1500	2.05	-6.22	7.51	-17.52
12	2	8000	2000	1.35	-2.58	6.47	-16.21
13	2	12000	1000	1.70	-4.60	7.37	-17.35
14	2	12000	1500	2.76	-8.81	11.35	-21.10
15	2	12000	2000	2.27	-7.11	9.24	-19.31
16	2	16000	1000	1.26	-2.02	6.34	-16.04
17	2	16000	1500	1.71	-4.64	8.30	-18.39
18	2	16000	2000	1.99	-5.98	8.05	-18.11

The optimal cutting performance for R_a was obtained for tool clearance strategy of an offset (Level 2), 16,000 rpm spindle speed (Level 3), and 1000 mm/min feed rate (Level 1) setting (A2B3C1). Table 3 shows the response table mean *S/N* ratio (signal refers to the desired real value, whereas noise refers to the undesired factors in measured values) for R_a and R_z.

Table 3. Response Table Mean *S/N* Ratio for R_a and R_z

Symbol	Parameter	Mean *S/N* Ratio			
		Level 1	Level 2	Level 3	Max-min
R_a (Smaller is Better)					
A	Tool Clearance Strategy	-5.435	-5.319		0.116
B	Spindle Speed (rpm)	-5.377	-6.588	-5.854	1.211
C	Feed Rate (mm/min)	-4.533	-5.854	-5.743	1.321
Rz (Smaller is Better)					
A	Tool Clearance Strategy	-18.51	-18.06		0.45
B	Spindle Speed (rpm)	-18.25	-19.15	-17.44	1.71
C	Feed Rate (mm/min)	-17.81	-18.48	-18.56	0.75

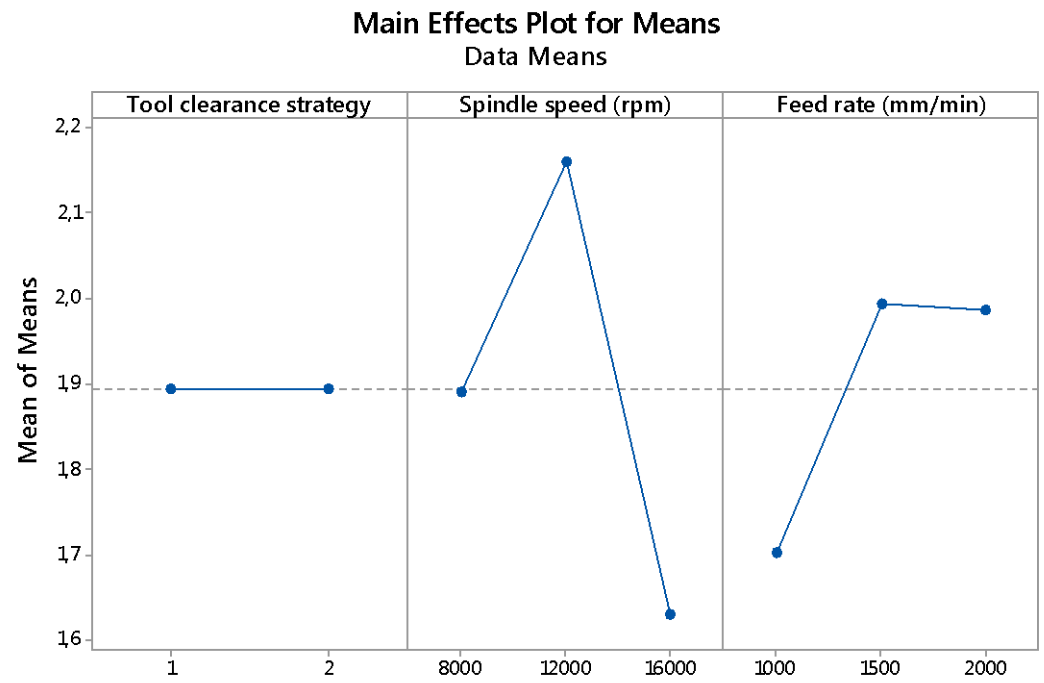
When analyzing the main effect plot for R_z (Figs. 3a and 4a), the raster tool clearance strategy obtained a smoother surface than the offset tool clearance strategy. Surface roughness values decreased with the decreasing feed rates. In the same way, many researchers have reported the effect of feed rate on surface roughness in wood and wood-based materials machining. According to the obtained results, the surface roughness decreases with increasing spindle speed and increases with the feed rate (Iskra and Tanaka 2005; Salca *et al*. 2008; Davim *et al.* 2009; Sutcu and Karagoz 2012; Sutcu 2013). Additionally, some researchers have explained that cutting speed has no effect on surface properties for large ranges of speed. Others reported that cutting speed has a slight effect depending on the process conditions (Costes and Larricq 2002). The value of surface roughness is higher at 12000 rpm than 8000 rpm. In contrast, at 16000 rpm, the surface roughness increased, even though it was expected to decrease.

Analysis of Variance (ANOVA)

ANOVA was conducted for a 95% confidence level. The factors did not exhibit statistical significance at a 95% confidence level. Effects of the tool clearance strategy, spindle speed, and feed rate on surface roughness were minimal (Table 4).

Table 4. ANOVA Results for R_a and R_z

Source	Degrees of Freedom (DoF)	Sequential Sum of Squares	Mean Sum of Squares	F-test	P – Coefficient
Ra (for *S/N* ratios)					
Tool Clearance Strategy	1	0.00000	0.000001	0.00	0.998
Spindle Speed (rpm)	2	0.84178	0.420890	3.61	0.059
Feed Rate (mm/min)	2	0.32584	0.162921	1.40	0.285
Residual Error	12	1.40023	0.116686		
Total	17	2.56785			
Rz (for *S/N* ratios)					
Tool Clearance Strategy	1	0.6429	0.6429	0.39	0.543
Spindle Speed (rpm)	2	8.4724	4.2362	2.58	0.117
Feed Rate (mm/min)	2	2.2188	1.1094	0.68	0.527
Residual Error	12	19.7204	1.6434		
Total	17	31.0145			



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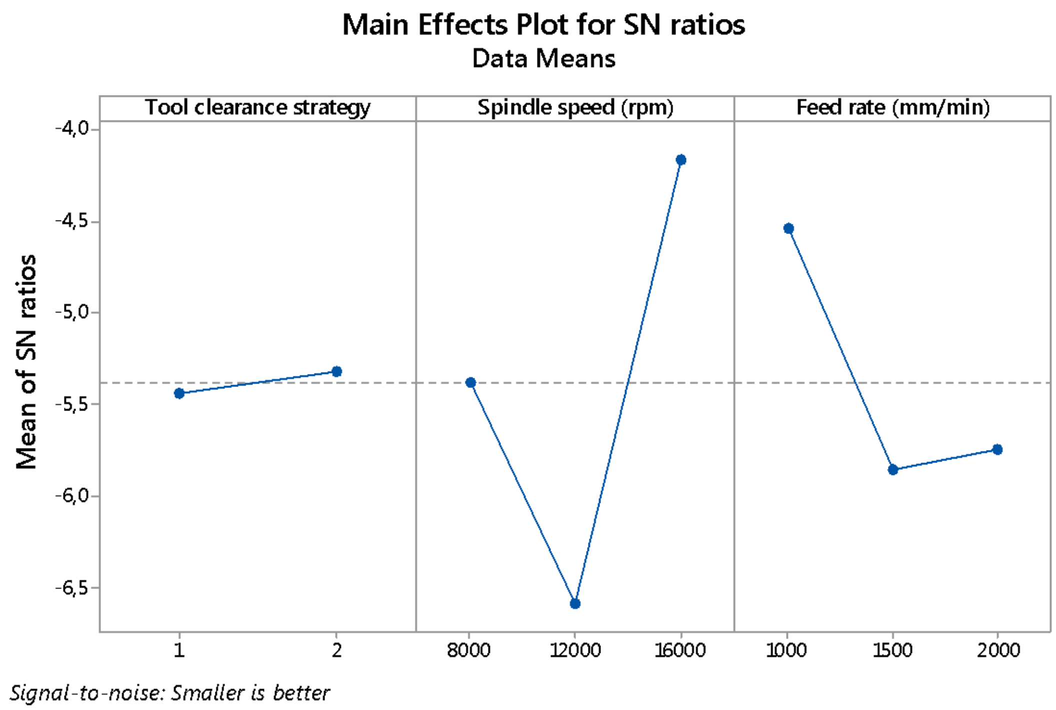

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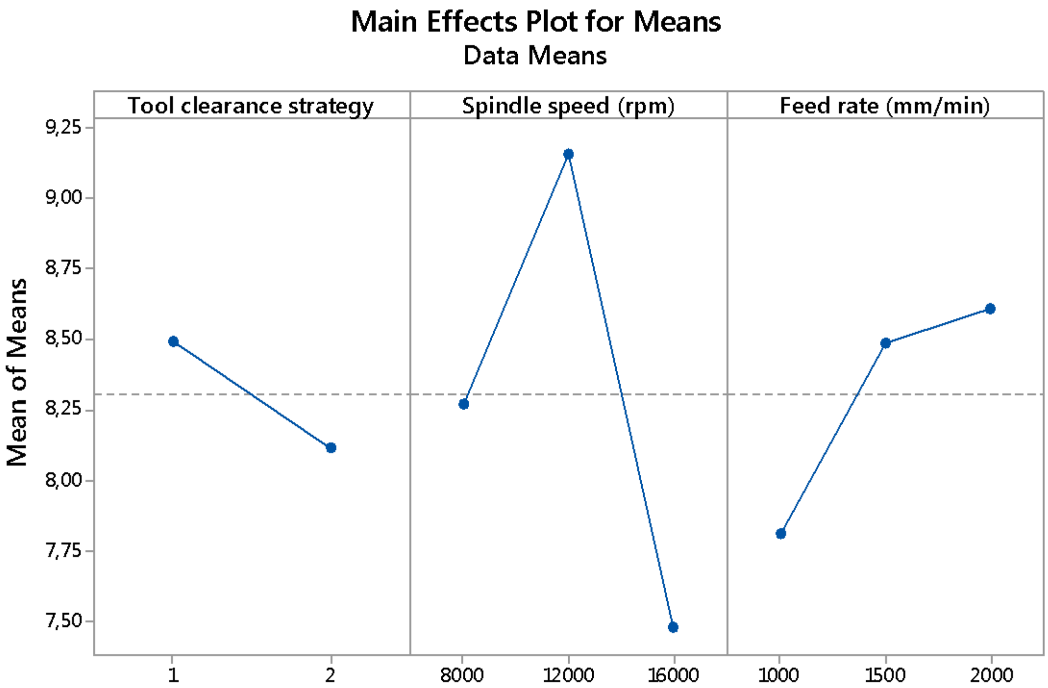
Fig. 3 (a) Main effect plot for means (surface roughness for R_a); (b) mean *S/N* ratio for surface roughness for R_a



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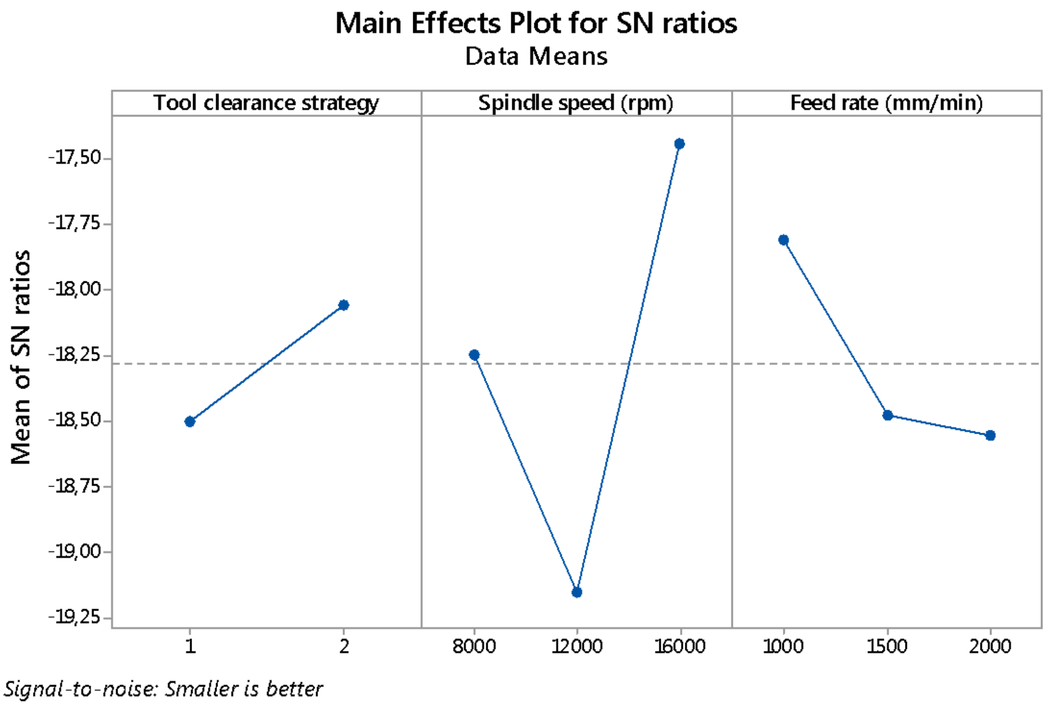

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Fig. 4. (a) Main effect plot for means (surface roughness for R_z); (b) mean *S/N* ratio for surface roughness for R_z

Confirmation Tests

Once the optimal levels of design parameters were chosen, the final step was to predict and verify the improvement of the performance characteristics using an optimal level of machining parameters at TM_{18}. An optimum agreement was observed between the predicted and real machining performance (Table 5). An increase in the *S/N* ratio from the initial machining parameters to the optimal cutting parameters (tool clearance strategy of an offset, 16,000 rpm spindle speed, 1000 mm/min feed rate) for R_a was 6.79 dB and for R_z was 5.06 dB. Based on the confirmation tests, R_a decreased 2.2 times and R_z 1.8 times compared to the starting cutting parameters.

Table 5. Confirmation Tests for R_a and R_z

	Starting Cutting Parameters	Optimal Cutting Parameters	
		Prediction	Experimental
R_a			
Level	A2B2C2	A2B3C1	A2B3C1
Surface Roughness (R_a) µm	2.758286	1.44044	1.262143
S/N Ratio (dB)	-8.8127	-3.26411	-2.0211
Improvement of *S/N* Ratio	6.7916 dB		
Prediction Error (dB)	1.24		
R_z			
Level	A2B2C2	A2B3C1	A2B3C1
Surface Roughness (R_z) µm	11.35486	6.79933	6.339714
S/N Ratio (dB)	-21,1036	-16.7463	-16.0414
Improvement of *S/N* Ratio	5.0622 dB		
Prediction Error (dB)	0.7049		

CONCLUSIONS

The following conclusions can be drawn from the surface roughness (for R_a and R_z) aspects, based on the experimental results obtained for the wooden edge glued panels (EGP) made of European larch (*Larix decidua* Mill.):

1. The surface roughness, both R_a and R_z, increased with increasing feed rate.
2. Both of the R_a and R_z surface roughness values for 12000 rpm is higher than 8000 rpm and 16000 rpm spindle speed. Smoothest surface was obtained 16000 rpm spindle speed.
3. The Taguchi design analyze method is suitable for solving the wood machining problems by CNC router machining which they were described in the present works. Better results have been obtained in terms of techniques such as Taguchi design method using MINITAB software.
4. The surface roughness; parameters for R_z for an offset cutting strategy is smoother than that of a raster cutter strategy. Parameters for R_a approximate values were obtained.
5. Optimal cutting performance for R_a and R_z was obtained for at a tool clearance strategy of an offset 16000 rpm spindle speed and 1000 mm/min feed rate cutting settings.
6. Based on the confirmation tests, R_a decreased 2.2 times and R_z 1.8 times compared to the starting cutting parameters.

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