PRODUCT DEVELOPMENT FROM VENEER-MILL RESIDUES: AN APPLICATION OF THE TAGUCHI'S METHOD

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ABSTRACT

The raw material used for decorative (face) veneer manufacturing consists mainly of hardwood logs, the highest in quality harvested for industrial purposes. Besides the common sawmill residuals, the clipping operation in the process produces quite long, strand-type vestiges, and large end-clipping cutoffs. During the course of the research project presented in this article, structural composite materials were designed and formulated using these clipping residues as principal furnish materials. A robust statistical product development technique, the Taguchi's method, helped to identify the effect of component factors on the expected mechanical properties of these novel products.

Results of three-factor/three-level analyses indicated that there is a linear positive correlation between target density and performance attributes (MOE and MOR). Increasing the content of end-clippings up to 25% resulted in decline of strength and stiffness. However, when the ratio was over 1 to 4, this trend proved to be negligible. Resin solid content within the selected range had no significant control over the examined panel properties.

Keywords: Veneer residues, composites, Taguchi's method, strength and stiffness, statistical process control, robust parameter design.

INTRODUCTION

Traditionally, solid wood is the most frequently used raw material for residential and commercial construction in the United States. During the last three decades, however, the increasing need for construction materials coupled with the decreasing quality and quantity of available raw materials triggered innovation and research work to meet challenges of demand and supply. Structural composite lumber materials (SCL) evolved that usually exhibit higher and more consistent mechanical properties than those of solid wood.

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A few years ago Smulski (1997) assembled an up-to-date compendium of wood-based structural composite manufacturing practices and demonstrated the current significance and prosperous future of the industry. Furthermore, Winandy (2002) identified four critical issues that the forest products industry has to deal with at the beginning of the third millennium. These include: demand for engineered systems; demand for durability; forest resources and management; public and user perceptions. This report argues that the above issues will mandate the increased use of SCL products including recycled composites, wood-cement systems, and structural fiberboards. Another study by the APA, The Engineered Wood Association, predicted a 4% annual increase through 2008 in demand for structural composite materials (Adair 2003).

It does appear that current research and development projects concentrate on wood-plastic composites (WPC). These are combinations of thermoplastic matrix materials (usually polyethylene/polypropylene) and wood flour or fiber. However, in these composites the exploitation of the natural strength and stiffness of wood in the direction of its grain is limited because of the small particle size. Some research and development has been reported in commercial journals with small diameter plantation trees from which the long, crushed fibers are reconsolidated into structural composite lumber (*TimTek*, formerly *Scrimber*). The concept is almost thirty years old, which clearly indicates slow progress in commercialization (Jarck and Sanderson 2001). Although the wood-based composite and polymer-manufacturing industries with the aid of research institutions have made significant progress in using low quality fiber-based materials, there is still a great potential to enhance the exploitation of our renewable natural resources.

BACKGROUND

Decorative (face) veneer manufacturing processes convert high quality half or quarter logs, with an average length of 3-4 m, into thin (0.5-0.8-mm) veneer sheets, sometimes referred to as veneer "leafs," by slicing or eccentric rotary peeling. Figure 1a schematically illustrates the slicing process. After drying and stacking, a clipping operation (Fig. 1b) sets the final rectangular dimensions of the veneer bundles that contain 15 to 20 sheets. During this operation, residual side-clippings, with an average length of 1-4 m and width of 25 to 40 mm, are produced. Moreover, the end-clipping operation generates rectangular-shaped cutoffs that can be easily converted into strand-type raw furnish for further composite manufacture. Figure 2 shows these typical veneer residues obtained from local mills in West Virginia. Surprisingly, these wastes are habitually used as fuel for energy generation—usually with low efficiency—or are being further processed to create landscaping mulch. Only ten percent of the clippings are being converted into fiber (Hassler 2002).

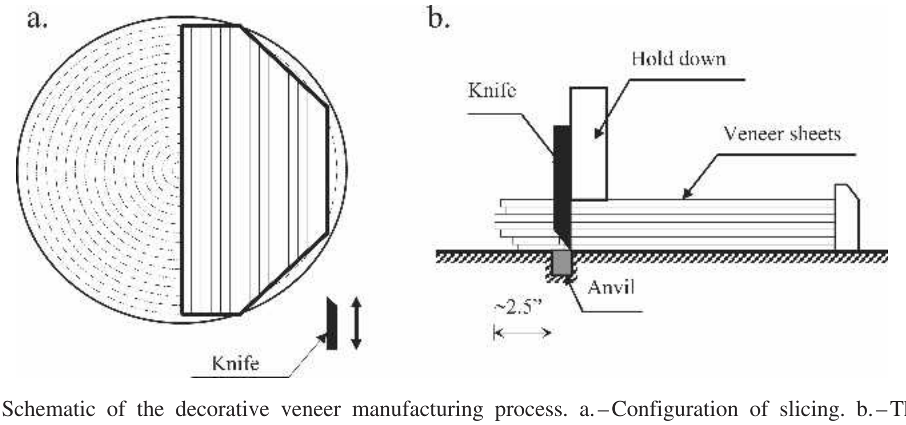

FIG. 1. Schematic of the decorative veneer manufacturing process. a.–Configuration of slicing. b.–The clipping operation.

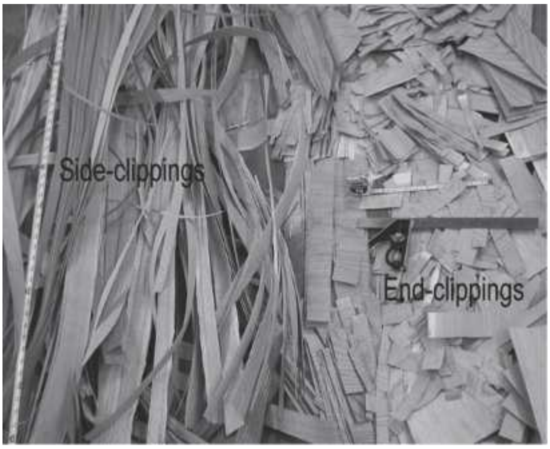

FIG. 2. Typical clipping residues generated by face veneer manufacture.

In 2002, a short-term research project was completed at the Division of Forestry, West Virginia University. The work was sponsored by the State of West Virginia, Research Challenge Grant Program. Objectives of the research included: (1) to obtain information about the yearly volume, species specification, and dimensions of veneer wastes in the Appalachian region via professional survey; (2) to develop laboratory-scale technology for manufacturing value-added products from these mill wastes; and (3) to determine the competitive mechanical properties of the new products.

The professional survey (Hassler 2002) revealed that in the central Appalachian region, 15 veneer mills generate approximately 60,000 metric tons of clipping residues annually. This volume corresponds to 92,000 m^3 ($\sim 30 \times 10^6$ board feet) wood-based composite materials on a 650 kg/m^3 average density basis. More than half of the responding companies use dry clipping procedures yielding residuals that have about 8% to 11% moisture content. The rest of the clippings have moisture contents around and above the fiber saturation point (FSP ~28%). Assuming the Appalachian mills are representative of all veneer mills in the United States and Canada, it can be roughly estimated that more than a quarter million tons of veneer residues are produced annually at almost one hundred veneer mills in North America.

The experimental and development parts of the mentioned study resulted in two characteristic structural composites designated as veneer strip panels (*VSP*) and veneer strip lumber (*VSL*). Side- and end-clippings were reconstituted into discrete composite panels and load-supporting SCL slabs by traditional hot-pressing consolidation processes. The resin application happened through roller coating and drum blending using conventional phenol-formaldehyde (PF) and polymeric diphenyl-methane-diisocyanate (pMDI) resins common in structural panel and SCL manufacturing. Standard ASTM testing procedures (ASTM D-143 1996a and ASTM D-1037 1996b) on limited sample sizes included apparent modulus of elasticity (MOE) and bending strength (MOR) determinations. Furthermore, internal bond (IB) tests demonstrated excellent strength values in the direction perpendicular to the principal plane of the materials (Lang and Denes 2002). Figure 3 shows the furnish materials and a set of composites that were used to investigate the viability of Taguchi's method in the product development process.

Characterization of multilayered, strand-type composites represents real challenges because of the extreme variations in physical and mechanical properties of the constituents. Further inconsistencies may originate from uneven resin distribution and from the more or less stochastic nature of different forming processes. Experimental design techniques can be very useful in

FIG. 3. Furnish materials and the composite products.

establishing statistical control of a process influenced by numerous factors (Montgomery 1997a). These factors include controllable processing and material parameters, natural irregularities in material properties and in setting processing parameters. Furthermore, the so-called outer noise factors may also be encountered. Over the years, several experimental techniques have been developed. One of them is Taguchi's robust parameter design method, an experimental approximation to minimizing the expected value of target variances for certain designs and processes. During the course of the work presented here, our general goal was to develop and optimize strand-type composite materials using advanced statistical design and process control techniques.

Specific objectives of this part of the study included the investigation of the applicability of the Taguchi's method for the optimization of flexural properties of the new products; and empirical model development that can isolate the influence of the selected factors—within their setting range—on the bending properties. The remainder of this paper contains the discussion of theoretical background, experimental materials and methods including results, and model development.

THEORETICAL CONSIDERATIONS

Design of new products or development of existing ones plays a vital role in most industrial organizations. Consequently, the efficiency of the development process is the key to success. However, in product manufacturing processes, most of the faults and nonconforming products result from the design and development phase, but usually they are discovered and eliminated later during the final product control (Booker et al. 2001). To reduce the exponentially growing rectifying costs of harmful effects, more emphasis must be placed on the early design stage.

A significant proportion of the problems related to the quality properties of the products originates from the erratic variability of different factors. Thus, minimizing any controllable variability would improve the performance of the products. The manufacturing processes are influenced by numerous deterministic or stochastic factors, which significantly affect the performance characteristics of any new product. Some of these factors are controllable while others are not. These uncontrollable ones are referred to as noise factors. In this context, optimizing product/process performance means: (a) identifying the key variables that influence the quality characteristics; (b) determining the levels of controllable factors that optimize process or performance; and (c) selection of a combination of control variables at which the system is insensitive to variation in the noise factors. A product or process improved in this way is called robust and the methodology is known as robust parameter design (RPD). The technique was introduced by Taguchi (Taguchi 1987) to improve the quality of a product through minimizing the effect of the noise factors by changing the setting levels of controllable variables.

The method is related to the design of experiment (DOE) theory using orthogonal arrays to study the parameter space. Taguchi proposed the use of separate designs for the two types of variables: the controllable factors are placed in a so-called inner array, and the uncontrollable ones comprise an outer array. Experiments are completed according to the Cartesian product of these designs. To reduce the number of the experimental runs, one can use a combined array (Nair et al. 1992) that incorporates both controllable and noise factors. Depending on the setting levels of the variables, a first- or second-order response model is fitted through the experimentally obtained data. Sufficient degrees of freedom in the model allow the investigation of the curvilinear effect of the factors. The general regression model of a full-quadratic response surface is given as follows:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \varepsilon \qquad (1)$$

where y represents the predicted property, k is the number of variables (x_i), β's are the least square regression coefficients, and the term ε

denotes the random error assumed to be normally and independently distributed with mean zero and variance σ^2 *($N(0, \sigma^2)$).* Equation (1) stands for a quadratic surface in the k-dimensional space of input parameters where β_i, β_{ij} contribute to the deviations from average values.

After dividing the variables into controllable and noise factors (Montgomery 1999), the model in matrix form becomes:

$$y(x,z) = \beta_0 + \{x'\}\{\beta\} + \{x'\}[B]\{x\} + \{z'\}\{\gamma\} + \{x'\}[\Delta]\{z\} + \varepsilon \quad (2)$$

where:

β_0 – the overall mean effect;
x' – row vector of control factors $x' = \{x_1, x_2, \ldots x_{n1}\}$;
z' – row vector of noise factors $z' = \{z_1, z_2, \ldots z_{n2}\}$;
x and z – transpose (column) vectors of x' and z', respectively;
β – column vector containing the regression coefficients of the control factors;
B – an n_1 x n_1 matrix whose diagonals are the regression coefficients associated with the pure quadratic effects, off-diagonals represent the interaction effects;
γ – vector of regression coefficients for the main effects of the noise factors;
Δ – an n_1 x n_2 matrix of the control factors by noise factor interaction effects;
ε – random error.

This model doesn't contain the pure quadratic effects of the uncontrollable variables because of the general assumption that they play little role in making a product robust (Nair et al. 1992). After selecting the control and noise factors that affect the quality characteristics of the product, an appropriate experimental matrix is developed according to the orthogonal design generation rules (Adler et al. 1977). The specified experimental runs in the design matrix then will be completed in random order and may be repeated if necessary.

Data processing begins with the analysis of variances (ANOVA) to determine the significance of factors and interactions. Taguchi's philosophy assumes that the interactions are unimportant. Thus, he proposes design matrices with low resolution. However, if the design matrix is not saturated, the evaluation of some interaction effects can be made. Moreover, Taguchi defines a performance measure called signal-to-noise ratio (SN) derived from the quadratic loss function, which calls for simultaneous optimization of the mean and standard deviation. For different optimization problems, a number of distinct SN ratios exist depending on whether the quality characteristic should have a definite target level or, on the contrary, approaching an extreme either low or high value is more satisfactory. For mechanical properties, the larger-the-better case is appropriate and the corresponding ratio is defined as follows:

$$SN_L = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (3)$$

In this formula n is the sample size, and y_i's are the individual measurements. The estimated SN ratios are then analyzed using ANOVA techniques to isolate the settings of the control parameters that will yield robust performance. Montgomery (1997a) points out that the signal-to-noise ratio in the larger-the-better case couples dispersion and location effects and essentially measures location effect unless there are significant differences in the variances of the individual parameters at different settings of noise factors. Consequently, the use of SN_L ratio may not be effective in inference making. Nevertheless, after identifying the important variables that affect the process output, one can model the relationship between the influential input variables and the output quality characteristics. The model parameters are quantified using regression analysis. Predicted response values, generated by the obtained regression model, can be represented as response surfaces, and the optimal region or optimization direction (by steepest ascent) can be identified or assigned.

MODELING ASSUMPTIONS, METHODS, AND MATERIALS

An L_9 Taguchi type fractional-factorial design helped to evaluate the significant factors affecting the bending strength and stiffness of the new composites. In order to assess the flexural properties as a function of technological conditions, the adhesive content, final density, and the end-clipping content were selected as design variables at three levels summarized in Table 1. The selection of the number of setting levels was based on curvilinear relationships between resin content and strand length versus mechanical properties as reported by Barnes (2000 and 2001) for oriented strand-type composites. These controllable factors correspond to x_i' in the model (Eq. 2) as discussed above.

The L_9 design allows the evaluation of four factors. Therefore, beside the three controllable processing parameters, the unknown effects can be considered as pooled together along with the experimental error in column 4 of the design matrix. For model development the following noise factors were considered:

The inner noise factors included the bulk density variations (BDV) within the hand-formed panel mats. BDV originates from two sources, namely from the stochastic nature of the forming process (edge effect) and from the density variation of the furnish material (strands), including within-species and between-species variations as well. Furthermore, to obtain different bulk and eventually final densities of panels, different masses of wood particles are deposited in the same volume, creating environmental noise factors i.e., variations in processing conditions during the hot-pressing operation. These manifest as variations in pressure, variation of temperature gradient through the thickness, and variation of vapor pressure between and within panels.

The independent assessment of noise factor effects and real interaction effects calls for large experimental design. Because of technological and time constraints, only nine experimental runs were accomplished, which allowed the evaluation of the effects of three factors. In this experimental arrangement, two of the three factors are confounded with two-factor interactions, while the third factor is confounded with the three-factor interaction of all the three factors involved. This notion requires the assumption that, for this particular case, the interaction between resin content (A) and target density (B) is negligible. Results of previous experiments on similar products encouraged the acceptance of this assumption (Lang and Denes 2002). Our model does not address the three-factor interactions because of the widely accepted postulation that higher order interactions are negligible unless there is an *a priori* knowledge of their significance (Adler et al. 1977).

Further assumptions in model development were based partially on experimental results and on practical considerations. Heterogeneity in mat formation (BDV) resulted in increased horizontal density variances of panels. This fluctuation is not in interaction with resin content (factor B) for the same reason as density itself. Moreover, the comparison of densities obtained on within-panel specimens demonstrated similar variances for panels having different end-clippings content (Table 2). This fact indicated the lack of interaction between the noise factor and factor C, i.e., content of end-clippings.

The influence of density fluctuation is manifested in shift and increased dispersion of flexural properties. The well-known relationship between wood density and mechanical properties certainly justifies the use of linear regression technique to adjust properties within a limited

TABLE 1. *Experimental factors and their levels.*

Factors			Factor levels		
Symbol	Description	Unit	1	2	3
A	Resin content	%	5	8	11
B	Target density	kg/m^3	650	700	750
C	Ratio of end-clippings	%	0	25	50

range of final density. Consequently, MOE and MOR values were adjusted to expected values of target densities having natural variances only. These regression analyses were performed on data obtained by testing within panel subsamples. Thus, the same setting of the other processing parameters and the same environmental conditions were maintained.

Specimen preparation and manufacture during the experimental part of this project included the following. A mix of three dominant species for decorative veneer production were used as raw materials. These included about 60% black cherry (*Prunus serotina*), 35% red oak (*Quercus rubra*), and 5% maple (*Acer spp.*) for all panel types. The dry veneer residues did not undergo any manipulation or modifications and were used exactly in the form as they come from an Appalachian decorative veneer manufacturing plant. An industrial phenol-resorcinol formaldehyde type adhesive (50% solid content) provided adhesion between the constituents. The resin application took place in a laboratory, rotary-drum blender. Adhesive content, as levels 1 to 3 of factor A were 5.0%, 8.0%, and 11.0%, respectively. These percentages represent the resin solid-contents relative to the dry furnish mass.

Hand mat forming in an 80-cm × 72-cm forming box ensured high degree of control in parallel alignment of long strands. However, the inherent edge effect could not be eliminated. Target densities as levels of factor B were 650, 700, and 750 kg/m^3. The three mat configurations (levels of factor C) included: (1) 100% long strands fully aligned without layering; (2) 75% long strands aligned and 25% randomly oriented end-clippings as core layer; (3) 50% long strands and 50% end-clippings in the core.

Stop bars controlled the final thickness (18.5 mm) of the composite panels during the consolidation. A 200-ton capacity, one daylight, hydraulic hot-press applied the consolidation pressures to achieve the target densities. Press platen temperature was 135° ± 2°C for all panels with approximately 35 min closed time and a 2 to 5 min venting time. The consolidation pressure varied according to the target densities.

Figure 4 schematically demonstrates the possible 27 combinations of factors and levels. The symbols at particular nodal points represent actual experimental set-ups used to develop the models. The experimental design required the manufacture of nine composite panels. From each panel, 8 specimens (750 mm long, 76.2 mm wide) were cut and conditioned at 21° ± 3°C and 65 ± 1% RH prior to testing for bending strength and apparent modulus of elasticity. Because the manufactured panels were highly orthotropic composites, tests for mechanical properties were performed in the expected strength-direction, i.e., parallel to the face strand alignment. All tests followed the specifications of relevant standards (ASTM 1996a and 1996b).

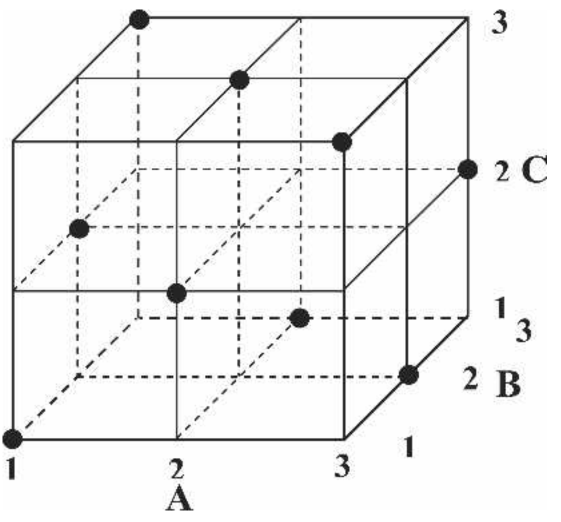

FIG. 4. Three-dimensional representation of the possible combinations of experimental set-ups. Nodes indicate the tested combinations.

The response surface methodology (RSM) made it possible to determine the optimum configurations for bending strength and stiffness. The interested reader can find the detailed description of this method in the literature (Meyers and Montgomery 2002; Montgomery 1997b).

RESULTS AND DISCUSSION

Table 2 summarizes the experimentally obtained physical and mechanical properties by factor/level combinations. These results demon-

TABLE 2. *Summary statistics of the experimental test results by factor/level combinations.*

Run number	Factors and levels A	B	C	n^a	Density $\bar{y}$ (kg/m^3)	COV^b (%)	Modulus of elasticity $\bar{y}$ (MPa)	COV^b (%)	MOE^c (MPa)	Modulus of rupture $\bar{y}$ (MPa)	COV^b (%)	MOE^c (MPa)
1	1	1	1	8	677	6.8	15351	11.3	14449	110	15.8	100
2	1	2	2	8	742	6.8	15478	10.5	14176	112	22.8	91
3	1	3	3	8	756	10.2	15125	16.9	14947	103	31.0	101
4	2	1	2	8	680	8.7	13516	15.9	12450	81	37.5	69
5	2	2	3	8	745	3.6	14582	5.6	13373	110	15.5	84
6	2	3	1	8	762	6.6	17671	7.6	17364	137	10.1	134
7	3	1	3	8	708	4.8	12879	10.4	10771	85	22.3	55
8	3	2	1	8	727	8.7	15554	11.4	14833	119	13.5	113
9	3	3	2	8	778	6.8	17087	7.7	16474	124	12.1	117
Overall average values:					730	—	15249	—	14315	109	—	96

$\bar{y}$-sample mean; a–sub-sample size; b–Coefficient of Variation; c–adjusted mean value.

strate the potentially superior mechanical properties of such novel composite products. The average MOE and MOR values of the new composites are very comparable to strength and stiffness of similar products currently on the market. Some increase in strength may be attributed to the densification beyond target values. However, after adjustments by regression technique, the strength and stiffness values still remained at very satisfactory levels.

Analysis of Variance (ANOVA) at significance level of $\alpha = 0.05$ identified the occurrence of statistical differences between the selected factors on the flexural properties. Having performed a three-level fractional factorial experiment and assuming high order interactions are negligible, it was possible to analyze the linear ($_L$) and the quadratic ($_Q$) effects of the factors. The results of ANOVA procedures in Tables 3 and 4 indicated that two main linear effects, final panel density and end-clippings content, may have significant influence on the flexural properties, which becomes evident after pooling the nonsignificant effects into the error term. Analyzing individually the marginal effects of factors (Fig. 5), it does appear that adhesive content in the selected range plays an insignificant role, while as demonstrated by other researchers, density has a positive linear effect on the examined mechanical properties

TABLE 3. *Results of ANOVA. The linear$_{(L)}$ and quadratic$_{(Q)}$ factorial effects on MOE.*

Factors		SS	df	MS	F	p	Effect	Std. err.
Mean value (MPa)							15249.2	275.9
Solid resin content	A_L	31302	1	31302	0.046	0.8506	−144.5	675.9
	A_Q	228	1	228	0.0003	0.9871	10.7	585.3
Final density	B_L	11035825	1	11035825	16.106	0.0568	2712.4	675.9
	B_Q	8925	1	8925	0.013	0.9196	−66.8	585.3
End-clipping content	C_L	5979711	1	5979711	8.727	0.0980	−1996.6	675.9
	C_Q	55345	1	55345	0.081	0.8030	166.4	585.3
Error		1370423	2	685211				
Total		18481758	8					
						$R^2 = 0.926$; $R^2_{adj} = 0.703$		
After pooling:								
Final density	B_L	11035825	1	11035825	45.160	0.00053	2712.4	403.6
End-clipping content	C_L	5979711	1	5979711	24.470	0.00259	−1996.6	403.6
Error		1466222	6	244370				
						$R^2 = 0.921$; $R^2_{adj} = 0.894$		

TABLE 4. *Results of ANOVA. The linear$_{(L)}$ and quadratic$_{(Q)}$ factorial effects on MOR.*

Factors		SS	df	MS	F	p	Effect	Std. err.
Mean value (MPa)							108.8	4.03
Solid resin content	A_L	1.3	1	1.3	0.009	0.9340	0.9	9.9
	A_Q	0.4	1	0.4	0.003	0.9642	0.4	8.6
Final density	B_L	1263.7	1	1263.7	8.645	0.0988	29.0	9.9
	B_Q	96.9	1	96.9	0.663	0.5010	7.0	8.6
End-clipping content	C_L	760.7	1	760.7	5.204	0.1501	–22.5	9.9
	C_Q	46.1	1	46.1	0.315	0.6309	–4.8	8.6
Error		292.4	2	146.2				
Total		2461.5	8					
						$R^2 = 0.881$; $R^2_{adj} = 0.525$		
After pooling:								
Final density	B_L	1263.7	1	1263.7	17.349	0.0059	29.03	7.0
End-clipping content	C_L	760.7	1	760.7	10.444	0.0179	–22.52	7.0
Error		437.0	6	72.8				
						$R^2 = 0.822$; $R^2_{adj} = 0.736$		

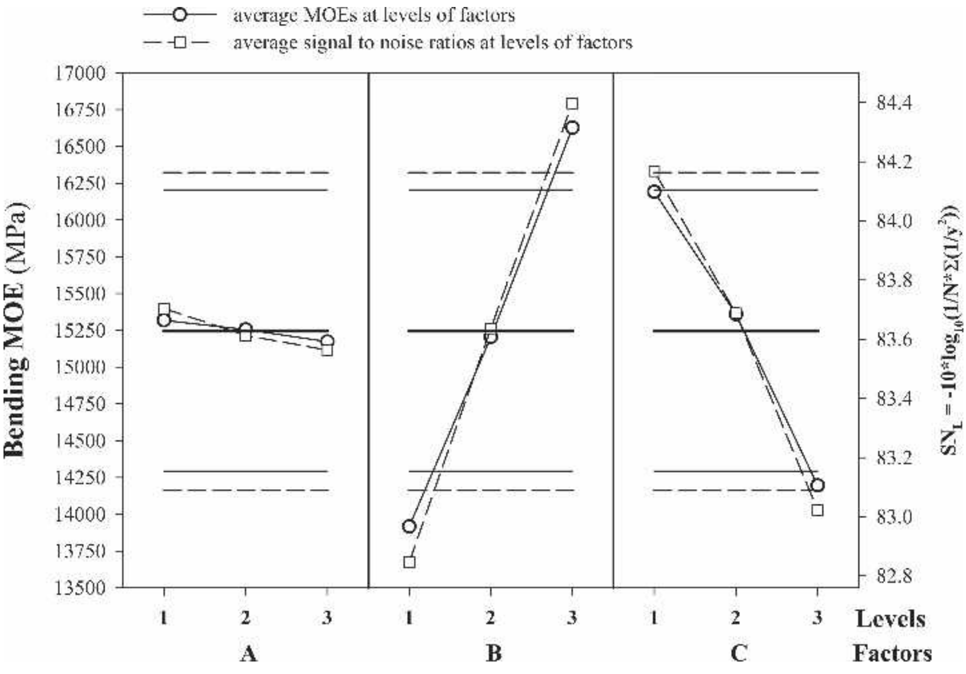

FIG. 5. Effect of factors on the modulus of elasticity. The predictions by mean values and SN_L ratios are compared. Horizontal lines represent mean values and ± 2 standard errors.

(Oudjehane and Lam 1998). In contrast, end-clipping contents have a near-linear negative effect on the expected stiffness of the products.

In Fig. 5, solid lines denote the experimental results; dashed lines represent the Taguchi's signal to noise ratios (SN_L) for the larger-the-better case. One can notice that both the experimental mean values and the SN ratios indicate the same trends in factorial effects as expected, i.e., none of the factors has any major effect on process variability; hence both the experimental means and SN_L ratios measure location effects only. Thus, the further use of signal-to-noise ratios in the analyses has been discontinued.

Solid lines in Fig. 6 show the effects of factors on MOR. The comparatively wide ranges of experimental errors (horizontal lines) make the significance of the linear factorial effects somewhat questionable. Quadratic effects—though visually detectable in the plots—proved to be statistically insignificant.

The designed target densities were exceeded in all cases by about 5 to 55 kg/m^3. As discussed earlier, MOR and MOE experimental values were adjusted to target densities. Dashed lines in Fig. 6 demonstrate the effects of factors on the bending strength after adjustment. As a result, the standard error of experiments decreased substantially. Tables 5 and 6 contain the results of ANOVA procedures performed on adjusted MOE and MOR data, respectively.

The modulus of elasticity and modulus of rupture quadratic response model equations in terms of factors and real number levels (Table 1), after adjustment to target densities, turned out to be as follows:

$$\hat{Y}_{MOE} = 44524 + 131.091A - 13.376A^2 - 120.696B + 0.113B^2 - 44.171C - 0.124C^2 \quad (4)$$

$$\hat{Y}_{MOR} = -232 - 1.447A + 0.064A^2 + 0.592B - 0.0001B^2 - 1.16C + 0.009C^2 \quad (5)$$

After pooling the nonsignificant effects in the residuals, the above regression models can be reduced to the following forms:

$$\hat{Y}_{MOE} = -10361.21 + 37.051B - 50.369C \quad (6)$$

$$\hat{Y}_{MOR} = -181.787 + 0.422B - 0.71C \quad (7)$$

The measuring unit of the predicted mechanical properties is MPa. The adjusted coefficients of determination values were 0.97 and 0.95 for MOE and MOR, respectively. These, along with other statistics, indicated that a high proportion of the deviation of measured and overall mean values of flexural properties can be explained by

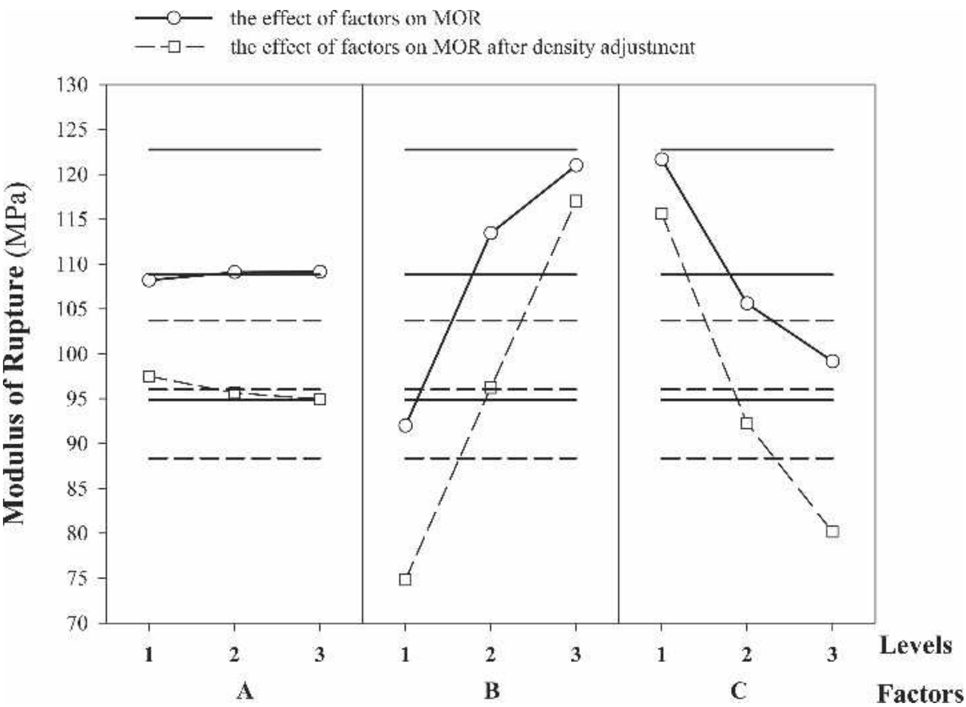

FIG. 6. Effect of factors on the modulus of rupture. Original and adjusted predictions are compared. Horizontal lines represent mean values and ± 2 standard errors.

TABLE 5. *Results of ANOVA. The linear$_{(L)}$ and quadratic$_{(Q)}$ factorial effects on adjusted MOE.*

Factors		SS	df	MS	F	p	Effect	Std. err.
Mean value (MPa)							14315.3	225.3
Solid resin content	A_L	371368	1	371368	0.813	0.4624	–497.6	551.8
	A_Q	28986	1	28986	0.063	0.8246	120.4	477.9
Final density	B_L	20591734	1	20591734	45.086	0.0215	3705.1	551.8
	B_Q	158700	1	158700	0.347	0.6153	–281.7	477.9
End-clipping content	C_L	9514049	1	9514049	20.831	0.0448	–2518.5	551.8
	C_Q	12007	1	12007	0.026	0.8861	77.5	477.9
Error		913437	2	456719				
Total		31590281	8					
						$R^2 = 0.971$; $R^2_{adj} = 0.884$		
After pooling:								
Final density	B_L	20591734	1	20591734	83.227	0.0001	3705.1	406.1
End-clipping content	C_L	9514049	1	9514049	38.454	0.0008	–2518.5	406.1
Error		1484498	6	247416				
						$R^2 = 0.953$; $R^2_{adj} = 0.937$		

TABLE 6. *Results of ANOVA. The linear$_{(L)}$ and quadratic$_{(Q)}$ factorial effects on adjusted MOR.*

Factors		SS	df	MS	F	p	Effect	Std. err.
Mean value (MPa)							96.02	2.2
Solid resin content	A_L	9.7	1	9.7	0.218	0.6863	–2.54	5.4
	A_Q	0.7	1	0.7	0.015	0.9138	–0.58	4.7
Final density	B_L	2673.9	1	2673.9	60.390	0.0162	42.22	5.4
	B_Q	0.2	1	0.2	0.004	0.9545	0.30	4.7
End-clipping content	C_L	1888.1	1	1888.1	42.642	0.0227	–35.48	5.4
	C_Q	63.4	1	63.4	1.431	0.3542	–5.63	4.7
Error		88.6	2	44.3				
Total		4724.4	8					
						$R^2 = 0.981$; $R^2_{adj} = 0.925$		
After pooling:								
Final density	B_L	2673.9	1	2673.9	98.775	0.00006	42.22	4.2
End-clipping content	C_L	1888.1	1	1888.1	69.746	0.00016	–35.48	4.2
Error		162.4	6	27.1				
						$R^2 = 0.966$; $R^2_{adj} = 0.954$		

the above regression equations. Equations (6) and (7) may be converted into multiple series of response surface plots, where one of the independent variables is fixed at a certain level, while the changes of the attribute in question are plotted as a function of the other factors. Figures 7a and 7b show the response surfaces for MOE and MOR at 8% fixed resin content (factor A) level. It is clear from the plots that the optimal process conditions, resulting in the best performance of the products, are the extremes of the tested intervals of the two factors (i.e., maximum density and minimum end-clipping content). However, the content of end-clippings influences the performance negatively at a far less rate than does the density in the positive direction. Contour plots in the *x-y* planes characterize the constant responses indicating that there are many combinations that may provide desirable performance of the products. The method of steepest ascent can determine the direction of maximum increase in response. However, in real-life optimization, several other related factors still need to be considered. These may include energy requirements, price and/or technological limitations, just mentioning a few.

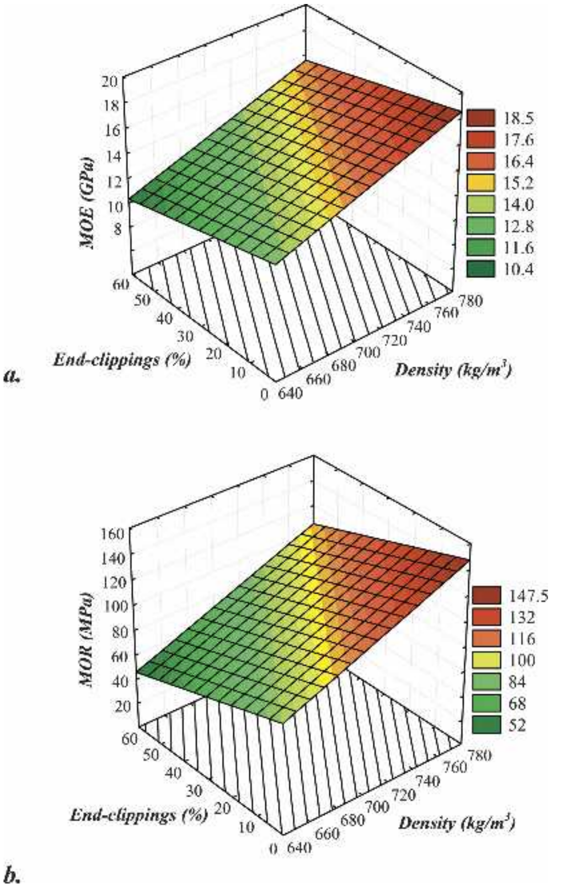

FIG. 7. Response surfaces predicting the expected mechanical properties as a function of factors B and C at fixed 8% resin content level. a. – Response surface of modulus of elasticity. b. – Response surface of modulus of rupture.

SUMMARY AND CONCLUSIONS

The applicability of the Taguchi's method has been investigated for the development of new structural composites. As previously had been verified, decorative hardwood veneer residues can be successfully converted into structural composites. Results of this segment of the research demonstrated that the flexural properties can be further manipulated to desired values by changing the levels of two key factors: density and short-furnish content. Analyses revealed that resin content had insignificant influence on strength and stiffness of the products within the examined range of levels. Contrary to our initial assumptions, the effect of the resin content and the quadratic effects of the other two factors (B_Q and C_Q) proved to be statistically insignificant within the selected variation intervals of the three factors.

Although the use of Taguchi's signal-to-noise ratios did not confer additional information for this particular case, the described statistical method to control manufacturing processes and the response surface models provided useful information for strand-type composite development. The advantages of these methods are the flexibility, expandability, and their strong statistical background. Currently, at the University of Western Hungary a seven-factor, two-level analysis for similar veneer-based products is in progress. Additional factors including wood species, consolidation temperature and pressure, strand geometry and strand orientation may provide better understanding of the relationships between technological parameters and performance of engineered wood composites.

Statistical quality control processes are increasingly gaining acceptance in the forest products industry. However, response surface models are rarely used in development of different structural composites. Expensive "trial and error" manufacturing runs can be avoided by screening out undesirable combinations of factors in the early stages of design and development. Only limited laboratory experiments and analytical works are needed to identify the combinations of processing variables that result in high performance characteristics. Regarding the current market, material supply and political circumstances, the authors hope that this work may help manufacturers in their efforts to maintain competitiveness and to improve the use of available resources.

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