# Effects of Fire-retardant Treatment and Burl Wood Structure on Three-dimensional Changes of Sandwich Panels Made from Walnut Decorative Veneer

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The effects of a fire-retardant treatment and burl wood structure on the three-dimensional changes of aircraft sandwich panels were evaluated. Unvarnished and varnished panels with an outer decorative layer made from walnut burl (*Juglans hindsii* L.) were studied. Half of the samples from each type of panel received a fire-retardant treatment (phosphate-based) on all three layers of the decorative plywood. The other half had the two inner layers treated and the outer layer was left untreated. Three different wood areas formed by rotary peeling and by the grain orientation from the burl structure were identified and their veneer surfaces were separately studied. Samples pre-conditioned at 20 °C and 40% relative humidity (RH) underwent adsorption (25 °C, 90% RH) and then desorption (25 °C, 40% RH) treatments. Changes in the moisture content (MC), swelling, shrinkage, roughness, and waviness were measured after each moisture exposure condition. The results showed that the fire-retardant treatment significantly increased the MC, swelling, shrinkage, roughness, and waviness of the unvarnished and varnished panels. This treatment also affected the roughness and waviness of the burl wood structure for the unvarnished panels. The effect of this anatomical feature was not noticeable in the varnished panels.

*Keywords: Aircraft furniture; Orange peel effect; Walnut burl; Fire-retardant treatment; Roughness; Waviness; Swelling; Shrinkage*

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## INTRODUCTION

Burl is a term generally used in the description of outgrowths developed at the stem base and woody tissue produced around stem wounds of trees and shrubs (James 1984). These formations are sometimes called wood tumors (Eroğlu and Gülsoy 2008; Saran *et al.* 2011), and they are generally induced by repeated disturbances, such as infections, fungal attack, and other unknown reasons (James 1984; Paula *et al.* 2016). Typically, all burls present an irregular grain, lack of orientation, and swirl and twist configurations in woody tissues compared with normal wood (Tsoumis *et al.* 1988). In some cases, the species may contain dark protuberances embedded within a matrix of woody tissue (El Mouridi *et al.* 2011). They may also contain numerous dormant buds and starch reserves, which are characteristics associated with sprouting. These structures are principally formed by parenchyma tissues (James 1984). This came to be considered an adaptive trait in ecosystems with highly frequent and severe disturbances, such as fire-prone ecosystems (James 1984). Wood burl properties differ noticeably from those of normal wood.

The fiber and vessel elements are remarkably shorter than in normal wood. The fibers have abnormal shapes, and the wood contains many extractives (Tsoumis *et al.* 1988; Saran *et al.* 2011). The density and volumetric shrinkage are higher in wood burls than in normal wood (Tsoumis *et al.* 1988; El Mouridi *et al.* 2011; Govorčin *et al.* 2012). The strength properties have more variability compared with normal wood, and they depend on the contorted fiber concentration of the outgrowth (Buchelt and Wagenführ 2007; Govorčin *et al.* 2012; El Alami *et al.* 2013).

However, no studies have been undertaken on the physical and mechanical properties of burls that contain dormant buds. Although burl structures have no appropriate properties for strength, they are particularly appreciated for their grain orientation, which produces visually attractive "figures" in veneers. According to Hoadley (2000), the term figure is used to refer to distinctive characteristic markings on side-grain surfaces of wood.

Thus, the walnut burl figure is prized for veneer productions. Twist and swirl figures are usually produced, but sometimes they are also accompanied by dormant buds, which create "eyes", making the burl even more aesthetically appealing. A burl veneer is used in high-quality automobile interiors, paneling and trim, inlays in doors, picture frames, and custom instruments (Buchelt and Wagenführ 2007).

For certain uses, decorative veneers, plywood, and other wood composites must be treated with fire-retardants. In particular, this treatment is required for materials with high surface flammability to enhance the properties of delayed ignition, reduced heat release rate, and slow diffusion of fire flames (ASTM E108 2013). Unfortunately, fire-retardant treatments usually lead to reductions in the strength properties, decrease the surface quality, increase the wood hygroscopicity, and change the dimensional stability of plywood panels (Ayrilmis *et al.* 2006; Dundar *et al.* 2008a,b; Candan *et al.* 2011; Rosero-Alvarado *et al.* 2017).

Aircraft furniture in the executive jet industry is manufactured with fire-retardant treated (FRT) decorative plywood. This type of wood panel is finished with a clear coating to improve the visual appearance, increase the durability, and protect the mechanical integrity of the decorative wood surface.

However, a defect called "orange peel" eventually appears on the surface of aircraft furniture, which is observed as a wavy surface on the varnish (Konieczny and Meyer 2012). Some authors define it as a surface with wavelengths greater than 1 mm (Guthrie and Weakley 1999). Other authors include short and long-term waviness (Kigle-Boeckler 1996; Love *et al.* 2001), which allow the characterization of the level of defect and definition of a tolerance.

Detecting the existence of orange peel and minimizing its effect is an important concern in the surface coating industry. Therefore, understanding the development of this defect and its relation to substrates is critical to quality control. This study evaluates the effect of a fire-retardant treatment and burl structure on the three-dimensional changes of aircraft sandwich panels in an attempt to understand the formation of orange peel. Unvarnished and varnished panels of walnut wood with a burl grain pattern were used for this purpose. Changes in the moisture content (MC), in-plane dimensions, roughness, and waviness were evaluated after exposure to adsorption and desorption treatments.

## EXPERIMENTAL

### Materials

*Decorative sandwich panels of aircraft furniture*

The sandwich panels in aircraft furniture used in this study were made with plywood, glued with a neoprene-based adhesive on a honeycomb panel (Nomex®, Core Composites, Bristol, Rhode Island, USA) and varnished with a polyester-based coating layer that was 450- to 535-µm thick. The plywood was composed of an outer decorative layer of walnut burl (*Juglans hindsii* L.) and two inner layers of poplar (*Populus sp*.). Each layer was 0.5-mm thick. For this study, two groups of sandwich panels, one with the three layers entirely treated (FRT) and the other with the two inner layers treated and the outer layer untreated (NFRT), were used. Veneers contained from 2.1 to 5.4 % ammonium polyphosphate $(NH_4PO_3)_n$ fire-retardant compound from a commercial supplier with a proprietary process, which was applied by immersion. Two groups of twenty for the FRT and NFRT panels were used. For each group, half of the panels were varnished with a clear coating, while the other half was kept unvarnished. From each panel, a sample 80 mm × 80 mm × 15 mm was cut for testing. All of the samples were pre-conditioned at 20 °C and 40% relative humidity (RH) until the moisture equilibrium was reached.

### Methods

*Surface preparation: Figures on the burl wood veneer surface*

The burl figure observed in the outer layer of the panels was obtained by peeling the burl outgrowth. The veneer was peeled parallel to the axis of the log (rotary cutting) and circumference of the burl (Booth 2008). Three areas within of burl figure were identified in this veneer: (i) a first burl area with short vessels, principally cut diagonally to the face grain (Z-axis), (ii) a second burl area showing long vessels, principally cut lengthwise, and (iii) a third burl area showing bud traces, as shown in Fig. 1a. Longitudinal sections 20-µm thick were cut from the each of the burl areas using a sliding microtome (Leica Microsystems, Nussloch, Germany). The sections were stained with safranin and temporarily mounted with 10% aqueous glycerin. Finally, they were observed with light microscopy, and images were taken using a Pixelink digital camera (Media Cybernetics, Rockville, MD, USA) for anatomical observation.

*Surface preparation: Square method*

For the unvarnished samples, four points that were spaced 11 mm apart and delimited the corners of a square, were marked on the surface of each burl area using a laser machine Model LMC 2000 (Beam Dynamics, Jacksonville, FL, USA), as shown in Fig. 1b. For the varnished samples, a square with 11-mm sides was drawn on the surface of each burl area with a laser machine (Fig. 1c). The depth of grooves of varnished surfaces did not exceed the varnish layer thickness. The areas within the squares were used to assess the changes in the dimensions and surface topography that resulted from the adsorption and desorption treatments.

*Adsorption and desorption conditioning treatments*

All of the sample edges were sealed with 3M 8067 tape to prevent moisture infiltration to the honeycomb. The samples were then conditioned in an environmental chamber for an adsorption treatment at 25 °C and 90% RH, until the moisture equilibrium was reached. Afterwards, the samples were re-conditioned for a desorption treatment at 25

°C and 40% RH. The changes in the MC of the samples were evaluated once equilibrium was reached. The gain and loss in MC of samples after adsorption and desorption were calculated based on the initial weight of the samples (at 20 °C and 40% RH) and the weight of sample after adsorption (25 °C and 90% RH) and desorption (25 °C and 40% RH), respectively, as shown in Eqs. 1 and 2,

$$\Delta MC_{ads}\ (\%) = (m_a - m_i) / m_i \times 100 \quad (1)$$

$$\Delta MC_{des}\ (\%) = (m_a - m_d) / m_d \times 100 \quad (2)$$

where $\Delta MC_{ads}$ is the gain in the MC (%) after adsorption at 25 °C and 90% RH, $\Delta MC_{des}$ is the loss in the MC (%) after desorption at 25 °C and 40% RH, $m_i$ is the initial weight (g) of the sample at 20 °C and 40% RH, $m_a$ is the weight of the sample (g) after adsorption at 25 °C and 90% RH, and $m_d$ is the weight of the sample (g) after desorption at 25 °C and 40% RH.

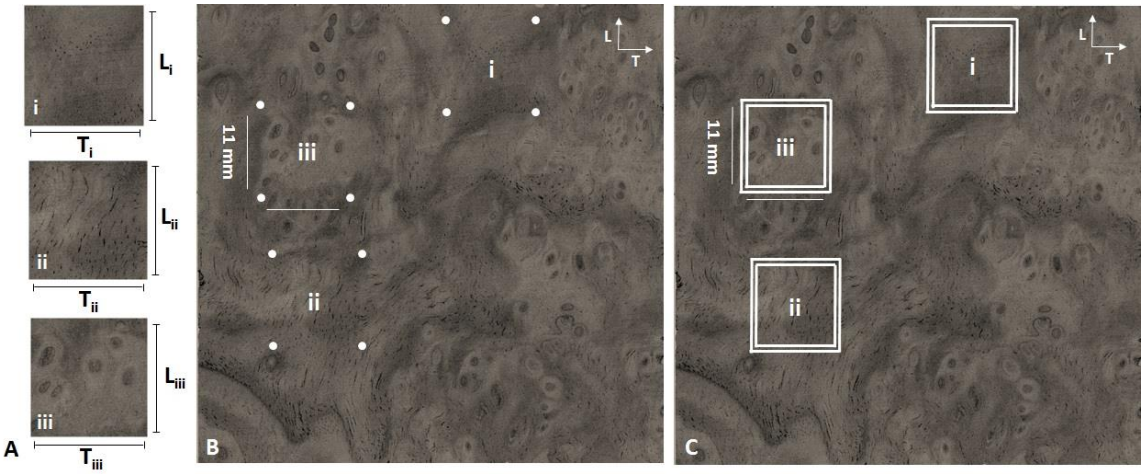


**Fig. 1.** Walnut burl figures (*Juglans hindsii* L.) obtained by rotary peeling; A: Transverse (T) and longitudinal (L) sides of burl areas i, ii, and iii; B: Set of four points spaced 11 mm delimiting the burl areas i, ii, and iii on the unvarnished panels; C: Square samples (11 mm) representing the burl areas i, ii, and iii on the varnished panels

*Dimensional changes of the sandwich panels*

The changes in the dimensions of the panels after adsorption and desorption were measured both in-plane and out-of-plane. The in-plane deformations were calculated in terms of percent swelling and percent shrinkage, whereas the out-of-plane deformations were evaluated in terms of the roughness and waviness variation.

*In-plane dimensional changes*

The swelling and shrinkage for the unvarnished samples were evaluated by the distance variation between two points. For the varnished surfaces, the in-plane dimensional changes were evaluated by the distance variation between the sides of the square. Changes in the transverse (T, X-axis) and longitudinal directions (L, Y-axis) of each sample were measured using a Stereo Discovery V8 microscope (Zeiss, Munich, Germany) coupled with a Axiocam ERc 5s camera (Zeiss, Munich, Germany). The data were then evaluated with Image pro plus 7.0v software (2015; Media Cybernetics, Rockville, MD, USA). The

percent partial swelling ($\alpha$) and percent partial shrinkage ($\beta$) in the T and L directions were calculated according to Eqs. 3 and 4,

$$\alpha_{T,L} = (D_{a(T,L)} - D_{i(T,L)}) / D_{i(T,L)} \times 100 \quad (3)$$

$$\beta_{T,L} = (D_{a(T,L)} - D_{d(T,L)}) / D_{a(T,L)} \times 100 \quad (4)$$

where $D_{a(T,L)}$ is the final dimension (µm) in the transverse or longitudinal directions after adsorption at 25 °C and 90% RH, $D_{i(T,L)}$ is the initial dimension (µm) in the transverse or longitudinal directions at the initial conditions of 20 °C and 40% RH, and $D_{d(T,L)}$ is the final dimension (µm) in the transverse or longitudinal directions after desorption at 25 °C and 40% RH.

*Out-of-plane dimensional changes*

The roughness and waviness parameters of the samples were measured at the initial state and after adsorption and desorption using a Micromeasure confocal microscope (Stil, Axe en Provence, France). Within each marked square, a surface of 10 mm (X-axis) by 10 mm (Y-axis) in the transverse and longitudinal directions of the sample was analyzed by Surface Map 2.4.13 software (Stil, Axe en Provence, France). The measurement steps were 100 µm and 50 µm in the X- and Y-axis, respectively. An acquisition frequency of 30 Hz and a scanning rate of 1.5 mm/s were used. Mountain Software (Digital Surf, Besançon, France) was used to calculate the roughness ($S$) and waviness parameters ($W$), according to ISO 4287 (1997). The mean surface ($S_a$, $W_a$), root mean square ($S_q$, $W_q$), maximum height of peaks ($S_p$, $W_p$), maximum depth of valleys ($S_v$, $W_v$), and total height peak to valley ($S_t$, $W_t$) were determined using a cut-off length of 0.8 mm combined with a Robust Regression Gaussian filter (ISO 16610-31 (2002)). This filter avoids the distortions produced by some filters when applied in profiles with deep valleys (Hendarto *et al.* 2006; Gurau *et al.* 2007; Tan *et al.* 2012). The core roughness depth ($S_k$, $W_k$), reduced peak height ($S_{pk}$, $W_{pk}$), and reduced valley depth ($S_{vk}$, $W_{vk}$) were calculated from the Abbot curve, according to ISO 13565-2 (1996). Finally, the changes or differences in each roughness and waviness parameter after adsorption and desorption were calculated using Eqs. 5 and 6,

$$\Delta S_{ads} = S_{ads} - S_i \quad ; \quad \Delta W_{ads} = W_{ads} - W_i \quad (5)$$

$$\Delta S_{des} = S_{ads} - S_{des} \quad ; \quad \Delta W_{des} = W_{ads} - W_{des} \quad (6)$$

where $\Delta S_{ads}$ and $\Delta S_{des}$ are the differences (µm) in the roughness parameters for adsorption and desorption, respectively, $\Delta W_{ads}$ and $\Delta W_{des}$ are the differences (µm) in the waviness parameters for adsorption and desorption, respectively, $S_{ads}$ and $W_{ads}$ are the roughness and waviness parameters (µm) after adsorption at 25 °C and 90% RH, respectively, $S_i$ and $W_i$ are the roughness and waviness parameters (µm) at the initial condition of 20 °C and 40% RH, respectively, and $S_{des}$ and $W_{des}$ are the roughness and waviness parameters (µm) after desorption at 25 °C and 40% RH.

*Experimental design*

Statistical analyses were done by means of the SAS package version 13.2 (SAS Institute Inc., Cary, NC, USA) (SAS 2014). A one-way analysis of variance (ANOVA) following the Mixed procedure was performed to assess the variation in the MCs with and without fire-retardant treatment after adsorption and desorption for the unvarnished and varnished panels separately. Given the number of surface parameters studied, a principal component analysis (PCA) was applied to the roughness and waviness data to regroup them

into common factors and facilitate their analysis. A PCA mathematically produces several linear combinations of observed variables, where each linear combination is a component. Variables that correlate with one another, but are largely independent of other subsets of variables, are combined into components (Tabachnick and Fidell 2007). The number of factors was estimated according to the Kaiser criterion, which only retains components with an eigenvalue greater than 1. The roughness and waviness changes (PCA results), swelling, and shrinkage were analyzed for each type of burl area (i, ii, and bud trace) at each conditioning treatment (adsorption and desorption) on the same specimen as a two-way repeated measures model with the Mixed procedure. Means difference comparison tests were performed to determine the significant differences at the 5% probability level when required. Finally, the normality of the data was verified using the Shapiro-Wilk test, and the homogeneity of variance was verified with the graphical analysis of residuals.

## RESULTS AND DISCUSSION

### Characterization of Walnut Burl Figure

The burl figure observed on the surface of the samples was characterized by a swirling grain around clusters of bud traces (Fig. 1). The color of the veneer was chocolate brown combined with yellowed brown or reddish brown, especially in the swirl grain zone. The vessels and bud traces contained gums, which emphasized the burl pattern.

Three distinct burl areas were identified on the walnut burl veneer. The first designated burl area (i) was characterized by the presence of ovoid pores formed by a high inclination of vessels with respect to the Z-axis. Inclined wood fibers and a large presence of parenchyma cells (Figs. 2a and 2b) were also observed in this section. The second burl area (ii) showed contorted fibers, contorted vessels cut lengthwise, wide rays, and a large presence of ray parenchyma viewed on the longitudinal section (Figs. 2c and 2d). Both burl areas were clearly observed on the swirl surface of the burl veneer. Thus, the wood orientation observed in burl areas i and ii was mainly associated with a high and low inclination of grain on the veneer surface (Z-axis), respectively. Finally, the third area (iii) showed several bud traces with different sizes, grouped in clusters surrounded by contorted xylem. Each bud trace included a pith surrounded by xylem and gums (Figs. 2e and 2f).

Burl structure characteristics, such as shorter fibers, shorter and wider vessels, and wider rays, suggest a high dependency on water availability or storage. The large amount of parenchyma may serve as storage for water, nutrients, and carbohydrates (James 1984). The swirl orientation, dormant buds, and starch reserves are characteristic of some burls that are associated with sprouting, and indicate an adaptation to very severe disturbances. According to Quinn (1990), the southern California walnut burl shields the meristematic tissue beneath the burls from fire. Later, sprouts surround this tissue resulting in multiple trunks.

### Moisture Content Changes of the Sandwich Panels

The ΔMCs of the unvarnished and varnished panels after each moisture exposure are presented in Table 1. The ANOVA indicated that the changes in the MC after adsorption or desorption were significantly affected by the fire-retardant treatment (data not shown). The ΔMCs were thus higher for the FRT panels than for the NFRT panels, for both sorption exposures. Moreover, the differences in the ΔMC between the FRT and NFRT panels were more apparent for the unvarnished panels than the varnished panels.

The ΔMC differences averaged 5.1% for the unvarnished panels and 0.7% for the varnished panels. The values for adsorption and desorption were pooled.

A similar behavior for the ΔMCs after adsorption and desorption was reported by Rosero-Alvarado *et al.* (2017) for Bubinga waterfall sandwich panels. In that study, the ΔMC differences between the unvarnished and varnished panels averaged 2.1% and 0.7%, respectively, which was a result of the fire-retardant treatment. The higher ΔMCs obtained in the present work for unvarnished walnut burl panels may have been because of the role played by the wood extractives, which are highly hygroscopic in this wood species (Cooper 1974).

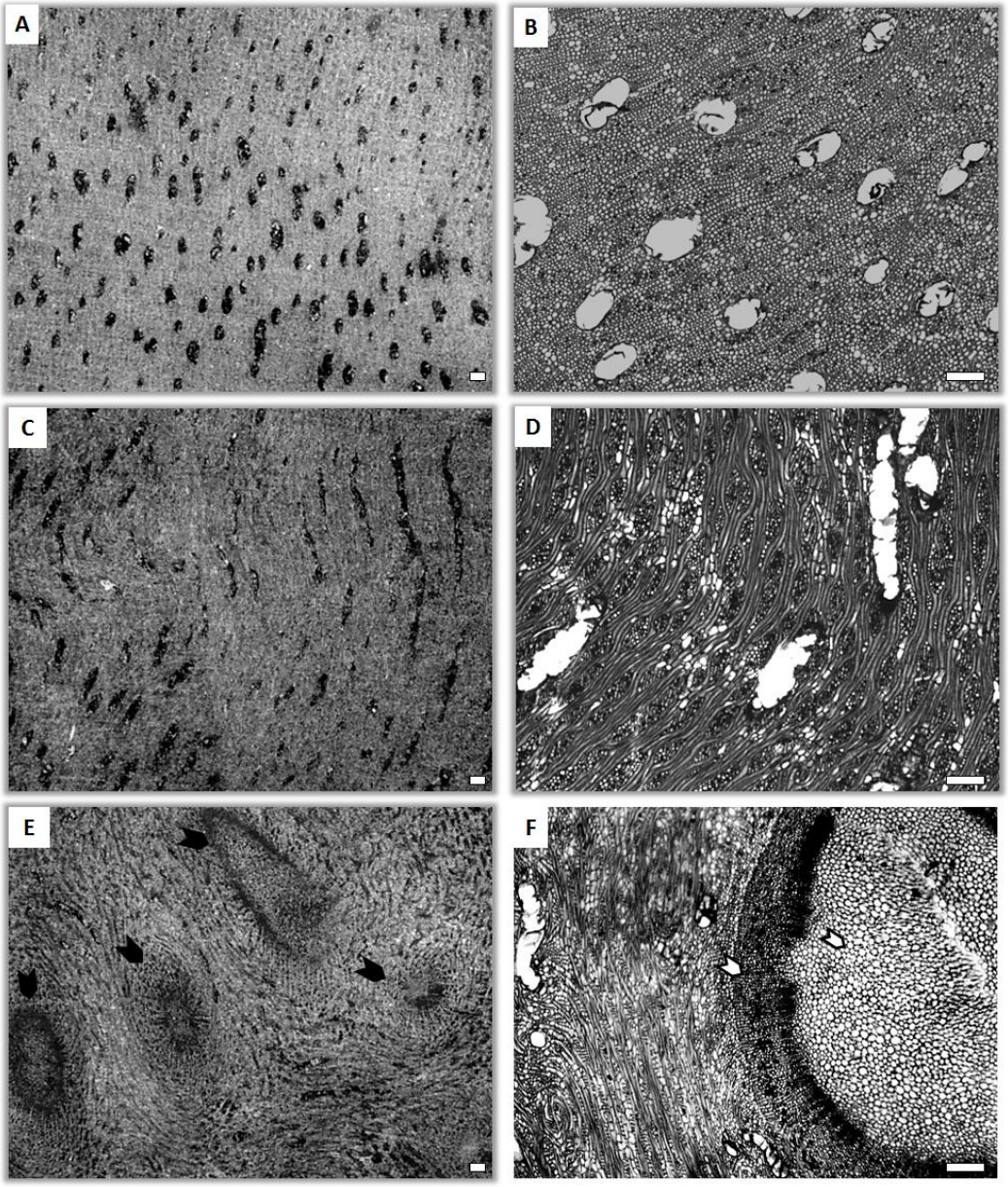


**Fig. 2.** Pictures of the walnut burl decorative veneer; A and B: Sections of burl area i; C and D: Sections of burl area ii; E: Section of bud area iii, where several bud traces are surrounded by contorted xylem (black arrows); F: Detail of E showing the pith and xylem of the bud trace (white arrows) and contorted xylem; scale bar 100 µm

After varnishing, the ΔMCs of the panels were similar for these two wood species (0.7% ΔMC). Previous works have reported that wood and wood-based panels treated with inorganic salts, such as boron compounds or phosphates, increase their hygroscopicity, particularly at high RHs (Dundar *et al.* 2009; Candan *et al.* 2011). Increases in the MC between 2% and 16% at a high RH have been reported for wood-based panels in several studies (Holmes 1977; Östman *et al.* 2001; Dundar *et al.* 2009; Candan *et al.* 2011). The increase of water adsorption could be attributed to the new adsorption sites that were formed by the treatment. The structural and chemical modification of cell-wall constituents may lead to the formation of additional hydrogen-bonding sites of water (Candan *et al.* 2011). In addition, increases in equilibrium moisture content of treated wood will depend on the type of chemical, level of chemical retention, size and species of the wood involved (Forest Products Laboratory 1999).

The ΔMCs were significantly lower in the varnished panels compared with the unvarnished panels. The lower ΔMC observed in the varnished panels can be explained by the sealing action provided by the coating film (de Meijer and Militz 1998; de Meijer and Militz 1999, 2001).

**Table 1.** Summary of the Moisture Content Changes (ΔMC) for the Unvarnished and Varnished Sandwich Panels after Adsorption and Desorption, and for the Fire-retardant-treated and Untreated Samples

| Treatment | Unvarnished Panels | | Varnished Panels | |
|---|---|---|---|---|
| | $\Delta MC_{ads}$ (%)[1] | $\Delta MC_{des}$ (%)[2] | $\Delta MC_{ads}$ (%)[1] | $\Delta MC_{des}$ (%)[2] |
| FRT | $7.8^{B3}$ (0.1) | $7.4^{B}$ (0.1) | $3.1^{B}$ (0.05) | $2.5^{B}$ (0.04) |
| NFRT | $2.8^{A}$ (0.02) | $2.2^{A}$ (0.01) | $2.3^{A}$ (0.02) | $1.8^{A}$ (0.02) |

[1]Increase in MC from the initial condition at 20 °C and 40% RH to 25 °C and 90% RH
[2]Decrease in MC from 25 °C and 90% RH to 25 °C and 40% RH
[3]Mean of 20 replicates; standard error of mean in parentheses; means within a column followed by different letters are significantly different at the 5% probability level

## Dimensional Changes of the Sandwich Panels

*In-plane dimensional changes*

The results of the in-plane dimensional changes for the unvarnished and varnished panels after adsorption and desorption are shown in Tables 2 and 3. The changes in the RH caused low swelling and shrinkage in the sandwich panels. Also, the deformations were equal in width (T) and length (L). Both observations were the result of the restraining and combining influence of the adjacent plies (three in this case) and glue lines composing the veneer. Previous works have reported a similar behavior for plywood with different numbers of plies and ply thickness (Lee and Biblis 1976; Lang and Loferski 1995). Furthermore, the sealing action of the coating film in the varnished panels caused lower in-plane hygroscopic deformation than in the unvarnished panels. Finally, because the ΔMCs were higher after adsorption than after desorption (Table 1), the dimensional changes in the T and L directions varied accordingly (Table 2).

The ANOVA showed that the swelling and shrinkage of the unvarnished and varnished panels were significantly affected by the fire-retardant treatment, as well as by the moisture exposure conditions (Table 3). The fire-retardant treatment significantly increased the dimensional changes of both panel groups in the T and L directions. These results were in agreement with previous works, which reported an increase in the swelling properties of wood-based panels treated with phosphate-based fire-retardant chemicals (Ayrilmis *et al.* 2006, 2007; Kartal *et al.* 2007; Rosero-Alvarado *et al.* 2017). The ANOVA also showed that the burl areas did not affect differently the in-plane dimensional changes of the sandwich panels (Table 3).

**Table 2.** Summary of the In-plane Dimensional Changes for the Unvarnished and Varnished Sandwich Panels after Adsorption and Desorption, and for the Fire-retardant Treated and Untreated Samples

| | | Adsorption (α) 25 °C, 90% RH | | Desorption (β) 25 °C, 40% RH | |
|---|---|---|---|---|---|
| | | Transverse Swelling (%) | Longitudinal Swelling (%) | Transverse Shrinkage (%) | Longitudinal Shrinkage (%) |
| Unvarnished Panels | Treatment | | | | |
| | FRT | $0.192^{B1}$ (0.005) | $0.195^{B}$ (0.005) | $0.170^{B}$ (0.005) | $0.168^{B}$ (0.005) |
| | NFRT | $0.154^{A}$ (0.004) | $0.161^{A}$ (0.004) | $0.140^{A}$ (0.004) | $0.137^{A}$ (0.004) |
| Varnished Panels | Treatment | | | | |
| | FRT | $0.139^{B}$ (0.004) | $0.136^{B}$ (0.004) | $0.127^{B}$ (0.003) | $0.125^{B}$ (0.003) |
| | NFRT | $0.094^{A}$ (0.003) | $0.084^{A}$ (0.003) | $0.066^{A}$ (0.002) | $0.066^{A}$ (0.002) |

Standard error of mean in parentheses; means within a column followed by different letters are significantly different at the 5% probability level

[1]Mean of 60 replicates; values of the three burl areas pooled; uppercase letters are for comparison within a column between fire-retardant treatments, for unvarnished and varnished panels separately

*Out-of-plane dimensional changes*

The results and analyses of the changes in roughness and waviness for the unvarnished and varnished panels after adsorption and desorption are shown in Tables 4 through 8. As was expected, changes in the RH caused variations in the surface topography of the panels. Similar to that observed for the in-plane dimensional changes, the out-of-plane dimensional changes were generally higher after the adsorption treatment than the desorption treatment, which corresponded with the ΔMCs. It was also clear that, because of the sealing action of the varnish, variations in the roughness and waviness were lower for the varnished surfaces than for the unvarnished surfaces.

**Table 3.** F-values Obtained from ANOVA of the In-plane Dimensional Changes of the Unvarnished and Varnished Sandwich Panels

| Source of Variation | | Unvarnished Panels | | Varnished Panels | |
|---|---|---|---|---|---|
| | DF | T[1] | L[1] | T | L |
| Treatment (*T*) | 1 | 8.3** | 12.8** | 315.5** | 242.1** |
| Burl Area (*B*) | 2 | 2.0 | 2.0 | 0.8 | 1.9 |
| *T* × *B* | 2 | 0.4 | 0.3 | 0.1 | 1.9 |
| Sorption Condition (*C*) | 1 | 17.7** | 36.0** | 114.4** | 56.2** |
| *T* × *C* | 1 | 1.1 | 0.0 | 46.1** | 14.0** |
| *B* × *C* | 2 | 0.1 | 1.0 | 0.5 | 3.5 |
| *T* × *B* × *C* | 2 | 0.2 | 0.4 | 0.1 | 2.0 |

* Statistically significant at the 5% probability level,
** Statistically significant at the 1% probability level
[1]T: Dimensional changes in the transverse direction of the sample; L: Dimensional changes in the longitudinal direction of the sample

**Table 4.** Factor Analysis Scores for All of the Surface Quality Parameters Following the Principal Components Initial Factor Method

| | Unvarnished Panels | | | | Varnished Panels | | |
|---|---|---|---|---|---|---|---|
| | Roughness ($\Delta S$) | | Waviness ($\Delta W$) | | Roughness ($\Delta S$) | | Waviness ($\Delta W$) |
| Variable | Factor 1 | Factor 2 | Factor 1 | Factor 2 | Factor 1 | Factor 2 | Factor 1 |
| $\Delta S_a$, $\Delta W_a$ | 0.66 | **0.72** | **0.88** | 0.36 | **0.72** | 0.63 | **0.85** |
| $\Delta S_q$, $\Delta W_q$ | **0.84** | 0.51 | **0.89** | 0.38 | **0.96** | 0.19 | **0.87** |
| $\Delta S_p$, $\Delta W_p$ | **0.83** | 0.31 | **0.92** | 0.34 | 0.02 | **0.70** | **0.92** |
| $\Delta S_v$, $\Delta W_v$ | **0.93** | 0.12 | 0.07 | **0.97** | **0.96** | 0.04 | **0.76** |
| $\Delta S_t$, $\Delta W_t$ | **0.96** | 0.17 | 0.62 | **0.77** | **0.90** | 0.24 | **0.91** |
| $\Delta S_k$, $\Delta W_k$ | 0.15 | **0.96** | **0.88** | -0.05 | 0.03 | 0.60 | 0.38 |
| $\Delta S_{pk}$, $\Delta W_{pk}$ | **0.70** | 0.36 | **0.82** | 0.17 | 0.17 | **0.87** | 0.29 |
| $\Delta S_{vk}$, $\Delta W_{vk}$ | **0.85** | 0.48 | **0.77** | 0.46 | **0.86** | -0.07 | 0.52 |
| Eigenvalue | 6.2 | 1.0 | 5.9 | 1.1 | 4.3 | 1.7 | 6.4 |
| % Variance | 77.2 | 11.6 | 73.9 | 14.2 | 54.4 | 20.8 | 80 |
| % Cumulative | 77.2 | 88.8 | 73.9 | 88.1 | 54.4 | 75.2 | 80 |

Factor loadings > 0.6 are shown in bold

The purpose of a PCA is to determine the number of common factors and their factor loading (Tabachnick and Fidell 2007). The factor loading, which is obtained for each component within the factors generated by the PCA, is a type of correlation coefficient in which a higher value is associated with greater significance. A factor loading value of 0.60

was selected as the lowest level for considering a given factor significant. The number of factors was defined according to the principal components initial factor method, with an eigenvalue greater than one (Table 4).

Thus, the PCA regrouped all of the roughness parameters that were studied into two common factors for the unvarnished and varnished panels. The waviness parameters were also regrouped into two common factors for the unvarnished panels and one factor for the varnished panels. For the unvarnished panels, the two factors explained 88.8% and 88.1% of the total variance in the roughness and waviness, respectively. For the varnished panels, the selected factors accounted for 75.2% and 80% of the total variance in the roughness and waviness, respectively. For both types of panels, Factor 1 was by far the principal contributor that explained the variations in the roughness and waviness (between 54.4% and 80.0% of the total variations). The factor loadings of the parameters composing Factors 1 and 2 varied between 0.60 and 0.97 (Table 4).

**Table 5.** F-values Obtained from PCA on the Changes in Roughness and Waviness for the Unvarnished and Varnished Panels

| | Unvarnished Panels | | | | Varnished Panels | | |
|---|---|---|---|---|---|---|---|
| | Roughness ($\Delta S$) | | Waviness ($\Delta W$) | | Roughness ($\Delta S$) | | Waviness ($\Delta W$) |
| Source of Variation | Factor 1[1] | Factor 2 | Factor 1 | Factor 2 | Factor 1 | Factor 2 | Factor 1 |
| Treatment (*T*) | 210.8** | 0.2 | 39.7** | 40.6** | 4.7*e | 7.5** | 0.1 |
| Burl Area (*B*) | 0.1 | 9.6** | 3.5* | 0.3 | 2.0 | 1.7 | 0.4 |
| T × F | 1.3 | 7.1** | 2.1 | 0.3 | 3.4 | 0.7 | 1.5 |
| Sorption Condition (C) | 76.9** | 2.1 | 66.3** | 20.8** | 22.7** | 279.1** | 573.4** |
| *T* × *C* | 32.1** | 2.0 | 7.3* | 7.2** | 8.2** | 54.8** | 116.9** |
| *B* × *C* | 1.9 | 0.2 | 3.2* | 0.2 | 1.8 | 1.1 | 2.6 |
| *T* × *B* × *C* | 2.7 | 1.6 | 3.4* | 7.6** | 1.2 | 0.4 | 0.7 |

* Statistically significant at the 5% probability level
** Statistically significant at the 1% probability level
[1]Roughness and waviness parameters included in each factor are shown in Table 4

The results of the ANOVA of the common factors of the roughness and waviness for the unvarnished and varnished panels are shown in Table 5. The fire-retardant treatment significantly affected the roughness and waviness of the unvarnished and varnished panels. These changes in the roughness and waviness were also significantly different after either adsorption or desorption. The burl area also affected the roughness and waviness, but for the unvarnished panels only. Several interactions between these three principal sources of variation (fire-retardant treatment, type of burl area, and exposure condition) were statistically significant (Table 5). These interactions indicated that changes in one of the independent variables affected the behavior of one of the other two variables, and therefore,

the behavior of the dependent variables. Thus, the interactions were taken into account when comparing the mean values of the three sources of variation. The mean comparison tests were performed by pooling the values of other sources of variation when possible. The results of the mean comparisons of the typical parameters of the roughness and waviness for the unvarnished and varnished panels are presented in Tables 6 through 8.

**Table 6.** Mean Difference Comparisons Performed on the Changes in Roughness (Repeated Measures) for the Unvarnished Panels

| Source of Variation | | Factor 1 | | Factor 2 | |
|---|---|---|---|---|---|
| | | $\Delta S_p$ (µm) | $\Delta S_{pk}$ (µm) | $\Delta S_a$ (µm) | $\Delta S_k$ (µm) |
| Treatment | Sorption Condition | | | | |
| FRT | Adsorption 25 °C, 90% RH | $54^{B1}$ (4) | $12.3^{B}$ (1.6) | | |
| NFRT | | $11^{A}$ (2) | $2.1^{A}$ (0.2) | | |
| FRT | Desorption 25 °C, 40% RH | $50^{B}$ (4) | $11.2^{B}$ (1.6) | | |
| NFRT | | $-1^{A}$ (2) | $-0.1^{A}$ (0.2) | | |
| Treatment | Burl Area | | | | |
| FRT | i | | | $23.3^{B\ b2}$ (1.9) | $6.0^{B\ b}$ (1.2) |
| | ii | | | $17.0^{B\ b}$ (1.8) | $4.2^{B\ b}$ (1.2) |
| | Bud Trace (iii) | | | $13.1^{B\ a}$ (1.5) | $2.1^{B\ a}$ (0.3) |
| NFRT | i | | | $1.7^{A\ a}$ (0.5) | $0.9^{A\ a}$ (0.2) |
| | ii | | | $1.9^{A\ a}$ (0.8) | $0.8^{A\ a}$ (0.2) |
| | Bud Trace (iii) | | | $0.8^{A\ a}$ (0.3) | $0.8^{A\ a}$ (0.1) |

Standard error of mean in parentheses; means within a column followed by the same letter are not significantly different at the 5% probability level

[1]Mean of 60 replicates; values of three types of burl area pooled; uppercase letters are for comparisons between the fire-retardant treatments, and for each exposure condition separately

[2]Mean of 40 replicates; values of moisture exposure conditions pooled; uppercase letters are for comparisons among the fire-retardant treatments for each burl area type separately; lowercase letters are comparisons between the types of burl area for each fire-retardant treatment separately

### Effect of the Fire-retardant Treatment

*Unvarnished panels*

The roughness parameters of Factor 1 were significantly higher for the FRT panels than for the NFRT panels, regardless of the exposure condition and type of burl area (Table 6). After adsorption, $\Delta S_p$ and $\Delta S_{pk}$ showed higher differences between the FRT and NFRT panels (among the six parameters regrouped in Factor 1). After desorption, differences in the roughness were even higher. This explained why the interaction of the fire-retardant treatment and exposure condition was statistically significant (Table 5).

**Table 7.** Mean Difference Comparisons Performed on the Changes in Waviness (Repeated Measures) for the Unvarnished Panels

| Source of variation | | | Factor 1 | | Factor 2 | |
|---|---|---|---|---|---|---|
| | | | $\Delta W_a$ (µm) | $\Delta W_k$ (µm) | $\Delta W_v$ (µm) | $\Delta W_t$ (µm) |
| Treatment | Burl Area | Sorption Condition | | | | |
| FRT | i | Adsorption 25 °C, 90% RH | 22.7$^{D}$ (2.5) | 2.11$^{D}$ (0.72) | 29$^{C}$ (5) | 77$^{C}$ (8) |
| | | Desorption 25 °C, 40% RH | 23.7$^{D}$ (2.7) | 2.63$^{D}$ (1.02) | 20$^{C}$ (4) | 65$^{C}$ (6) |
| | ii | Adsorption 25 °C, 90% RH | 15.2$^{C}$ (2.2) | 1.17$^{C}$ (0.32) | 27$^{C}$ (6) | 65$^{C}$ (8) |
| | | Desorption 25 °C, 40% RH | 15.0$^{C}$ (2.1) | 0.80$^{C}$ (0.33) | 29$^{C}$ (5) | 64$^{C}$ (8) |
| | Bud trace (iii) | Adsorption 25 °C, 90% RH | 11.4$^{C}$ (1.7) | 0.69$^{C}$ (0.07) | 29$^{C}$ (6) | 63$^{C}$ (10) |
| | | Desorption 25 °C, 40% RH | 10.2$^{C}$ (1.8) | 0.43$^{C}$ (0.07) | 25$^{C}$ (5) | 55$^{C}$ (10) |
| NFRT | i | Adsorption 25 °C, 90% RH | 3.1$^{B}$ (0.7) | 0.42$^{B}$ (0.03) | 5$^{B}$ (2) | 13$^{B}$ (3) |
| | | Desorption 25 °C, 40% RH | 0.2$^{A}$ (0.4) | 0.07$^{A}$ (0.02) | 1$^{A}$ (1) | 4$^{A}$ (4) |
| | ii | Adsorption 25 °C, 90% RH | 4.7$^{B}$ (1.0) | 0.44$^{B}$ (0.03) | 12$^{B}$ (4) | 22$^{B}$ (5) |
| | | Desorption 25 °C, 40% RH | 0.7$^{A}$ (0.8) | 0.02$^{A}$ (0.02) | 1$^{A}$ (4) | 2$^{A}$ (4) |
| | Bud trace (iii) | Adsorption 25 °C, 90% RH | 1.8$^{B}$ (0.3) | 0.44$^{B}$ (0.03) | 8$^{B}$ (2) | 14$^{B}$ (2) |
| | | Desorption 25 °C, 40% RH | 0.2$^{A}$ (0.2) | 0.10$^{A}$ (0.02) | 2$^{A}$ (2) | 3$^{A}$ (2) |

Mean of 20 replicates; standard error of mean in parentheses; means within a column followed by the same letter are not significantly different at the 5% probability level

The values obtained indicated that, after desorption, the roughness of the FRT panels almost returned to their initial values (positive values). In contrast, the roughness of

the NFRT panels after adsorption remained at the swollen state and did not suffer any changes after desorption (close to zero value). This behavior could have been related to the second-order effects of moisture sorption, which indicated that the transverse dimensions are greater after desorption than after adsorption (Hernández 1993; Arévalo and Hernández 2001). Thus, the second-order effects could have been smaller for the FRT panels than for the NFRT panels. Furthermore, the roughness parameters of Factor 2 ($\Delta S_a$ and $\Delta S_k$) were also higher for the FRT panels than for the NFRT panels. This was observed for all three types of burl areas (Table 6). Therefore, the fire-retardant treatment applied to the unvarnished panels increased the changes in roughness after adsorption and desorption, regardless of the burl area. The fire-retardant treatment also affected the waviness of the unvarnished panels (Table 4).

Table 7 shows that changes in the waviness parameters were always higher for the FRT panels than for the NFRT panels. This was observed for each type of burl area and exposure condition. These results were also in agreement with previous works (Ayrilmis *et al.* 2006, 2007; Kartal *et al.* 2007; Rosero-Alvarado *et al.* 2017).

*Varnished panels*

The roughness and waviness increased when the unvarnished wood was directly exposed to changes in the RH (moisture exposure condition). Once the varnish was applied to the surfaces, changes in the roughness and waviness after moisture exposure still occurred, but were lower. Nevertheless, the varnished wood surfaces were affected by the fire-retardant treatment.

The interactions between the fire-retardant treatment and exposure conditions for all of the roughness and waviness factors were statistically significant (Table 5). This indicated that the effects of the fire-retardant treatment on the roughness and waviness depended on the moisture exposure condition. Thus, changes in the roughness parameters of Factors 1 and 2 were statistically similar for the FRT and NFRT panels after adsorption (Table 8). However, after desorption, the roughness variation of the FRT panels was negative for both factors. At this condition, the FRT panels showed a higher variation in the roughness compared with the NFRT panels. The waviness values also showed the same behavior after desorption. The negative values of these parameters indicated that the changes in roughness and waviness that occurred after adsorption increased further following desorption. This unexpected result could have been because of the possible formation of microcracks on the wood-varnish interface during adsorption and desorption (Yalcin and Ceylan 2017). Microcracks were also induced during the production of plies by rotary peeling. According to Cool and Hernández (2011), microcracks can act as points of discontinuities during the moisturizing-drying cycles of weathering. Thus, these breaks in bonding can cause the changes in roughness and waviness of the varnish film to be less affected by the underlying wood layer. The results obtained after adsorption, being the first step of weathering, should be less affected by this behavior.

Taking into account the previous discussion, Table 8 expresses that the changes in waviness that occurred after adsorption were significantly higher for the FRT panels than for the varnished NFRT panels. Among all of the waviness parameters studied, $\Delta W_p$ and $\Delta W_t$ were more sensitive to differences between the fire-retardant-treated and untreated panels. Thus, $\Delta W_p$ and $\Delta W_t$ were 50% and 30% higher, respectively, for the varnished FRT panels than for the varnished NFRT panels.

## Effect of the Burl Figure Variation

The type of burl area also affected the changes in the roughness and waviness of the unvarnished panels produced by changes in the RH. However, this effect was only detected for the FRT panels. The higher values of $\Delta S$ and $\Delta W$ of these panels probably allowed for an easier differentiation among the types of burl areas. Thus, changes in the roughness parameters of Factor 2 were different among the three types of burl areas. The bud trace (iii) had the lowest changes in the $\Delta S_a$ and $\Delta S_k$ compared with the first (i) and second (ii) types of burl areas. For the waviness, the $\Delta W_a$ and $\Delta W_{vk}$ of the bud trace (iii) and second (ii) burl area were lower than those of the first (i) burl area. These rather higher changes in the roughness of the first (i) and second (ii) burl areas indicated a higher swelling in the Z-axis of the tissue zones dominated by fibers (swirl surface) compared with the zones dominated by parenchyma (bud traces), as illustrated in Fig. 2. In the case of the waviness, the higher values of the first (i) burl area compared with the second (ii) burl area were because of the different grain orientation of the veneer surfaces. A higher number of cross-cut wood cells was observed in burl area i, which could have contributed to a higher availability of sorption sites compared with burl area ii.

The waviness parameters used in this study can be successfully used to evaluate the so-called orange peel defect. This defect, used to describe the wavy appearance of a varnished surface, was observed on all of the panels studied. The higher variation in the waviness of the fire-retardant-treated panels compared with the untreated panels indicated that this treatment increased the extent of the orange peel defect. Among all of the waviness parameters studied, $\Delta W_p$ and $\Delta W_t$ resulted in the highest differences between the fire-retardant-treated and untreated panels after adsorption. Therefore, these parameters appeared to be the best descriptors of waviness in the varnished panels due to the fire-retardant treatment.

**Table 8.** Mean Difference Comparisons Performed on the Changes in Roughness and Waviness (Repeated Measures) for the Varnished Panels

| Source of Variation | | Roughness | | | | Waviness | |
|---|---|---|---|---|---|---|---|
| | | Factor 1 | | Factor 2 | | Factor 1 | |
| | | $\Delta S_a$ (µm) | $\Delta S_{vk}$ (µm) | $\Delta S_k$ (µm) | $\Delta S_{pk}$ (µm) | $\Delta W_p$ (µm) | $\Delta W_t$ (µm) |
| Treatment | Sorption condition | | | | | | |
| FRT | Adsorption 25 °C, 90% RH | $0.060^{A}$ (0.010) | $0.12^{A}$ (0.05) | $0.017^{A}$ (0.001) | $0.18^{A}$ (0.02) | $4.0^{B}$ (0.3) | $6.8^{B}$ (0.5) |
| NFRT | | $0.042^{A}$ (0.004) | $0.06^{A}$ (0.01) | $0.016^{A}$ (0.001) | $0.14^{A}$ (0.02) | $2.7^{A}$ (0.2) | $5.4^{A}$ (0.3) |
| FRT | Desorption 25 °C, 40% RH | $-0.070^{B}$ (0.010) | $-0.12^{B}$ (0.13) | $-0.014^{B}$ (0.001) | $-0.12^{B}$ (0.02) | $-2.2^{B}$ (0.3) | $-3.3^{B}$ (0.4) |
| NFRT | | $-0.003^{A}$ (0.003) | $0.03^{A}$ (0.02) | $0.011^{A}$ (0.001) | $0.03^{A}$ (0.01) | $-0.1^{A}$ (0.2) | $0.9^{A}$ (0.3) |

Means of 60 replicates; values of the three different burl areas pooled; standard error of mean in parentheses; means within a column followed by different letters are significantly different at the 5% probability level; comparisons between the fire-treatments were performed for each sorption condition separately

Further studies should be conducted to determine the impact of other types of chemicals as well as different retention and concentration levels of the treatment on the degree of the orange peel defect. It is clear that the decrease of the orange peel defect must be made while ensuring a suitable level of fire retardancy.

## CONCLUSIONS

1. The fire-retardant treatment had a significant effect on the MC, swelling, shrinkage, roughness, and waviness of the unvarnished and varnished walnut panels. These properties increased once the sandwich panels were treated with the fire-retardant chemical.
2. The fire-retardant treatment also produced a smaller variation in the roughness and waviness of the burl wood structure. The surfaces dominated by parenchyma (bud trace) had the lowest variations compared with other areas of the unvarnished veneer. However, the effect of the different areas of the burl figure on the surface topography was not discernible once the surfaces were varnished.
3. The sealing action of the varnish layer restricted and reduced changes in the MC, swelling, shrinkage, roughness, and waviness of the sandwich panels.
4. The orange peel defect was observed on the surfaces of all of the varnished panels as a result of the changes in the MC. This defect was more pronounced in the panels treated with fire-retardant chemicals.

## ACKNOWLEDGMENTS

The authors gratefully acknowledge Jean Ouellet and Luc Germain for their valuable assistance. This research was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), Mitacs accelerate program, Bombardier Aerospace, and 3M Canada.

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Article submitted: April 18, 2017; Peer review completed: June 29, 2017; Revised version received and accepted: July 12, 2017; Published: July 24, 2017.
DOI: 10.15376/biores.12.3.6471-6489