Water-Based and Solvent-Based Stains: Impact on the Grain Raising in Yellow Birch

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Water-based finishes are slowly replacing solvent-based finishes in the wood industry. Wood grain raising is an important issue associated with the use of water-based stains. In this paper, water-based and solvent-based stains were applied on yellow birch veneers and hardwood samples that had been previously sanded. Grain raising phenomena were studied by profilometry and microscopy. This study demonstrated that the appearance of wood surfaces treated with water-based and solvent-based stains is affected by a number of factors, including grain raising, surface preparation quality, and substrate type. Main observations are: 1) the sanding method has an important role in the grain raising generation and finish quality; 2) profilometry experiments revealed that developed interfacial area parameter can provide valuable information, as it captures both grain roughness and small-scale roughness due to raised fiber fragments; 3) differences between sawn lumber and peeled veneer appeared minor, although the lumber exhibited less significant differences between water-based and solvent-based finishing systems; and 4) wood fragments on the wood surface would be difficult to eliminate.

Keywords: Grain raising; Water-based stains; Profilometry; Wood surface preparation; Fibre fragments

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INTRODUCTION

Solvent-based finishes have long been the standard practice in a number of industries, including the secondary processing wood sector. Solvents are used to dissolve and disperse resins, pigments, and additives. They serve as a transfer vehicle for final application to the substrate. Organic solvents used in finishing products create issues with respect to the environment and human health, as well as handling and storage (Anon. 2010). As a result, European, American, and Canadian architectural regulations have recently been modified to restrict usage and encourage less hazardous alternatives.

The proposed alternatives entail significant disadvantages, and these restrict their adoption by the wood industry. One major such disadvantage relates to the appearance of water-based coatings, which typically differs from that of solvent-based coatings (Landry and Blanchet 2010). The literature cites several factors accounting for such appearance differences. They can be listed under two different headings. The first category includes factors relating to the wood/coating interface (*e.g.*, wood grain raising), while the second category consists of factors relating to the inherent properties of the finishing products.

The application of water or water-based finishes onto a sanded wood surface is known to raise the grain of the some woods (*e.g.*, cotton wood) more than others (*e.g.*, oaks) (Koehler 1932). Wetting induces the development of lint, thus increasing roughness. Grain raising varies with several factors, including: wood species; solids contents and surface tension of the finishing products; coating thickness; resin solubility and glass transition temperature; minimum film-forming temperature; drying speed and method; surface preparation; resin viscosity; resin application method; and ambient conditions (humidity and temperature) (van Ginkel 2002).

Despite being a common phenomenon, wood grain raising has attracted limited interest from the scientific community. The first published work on the topic (Koehler 1932), concluded that grain raising actually involves individual fibers, groups of fibers, or fiber fragments lifting as a result of wetting and sanding. Individual fibers tend to twist and lift as the wood dries down, with some species being more prone to grain raising than others. Grain raising also seems to relate to fiber damage caused by the sanding process.

Marra's group (Marra 1943) identified three main causes for grain raising: cell wall collapse, swelling of sanded fibers, and inter-fiber separation. They have also shown that sanding perpendicular to fibers leads to greater grain raising, that grain raising is more pronounced on the pith side of a board than on the bark side, and that the degree of grain raising varies with the roughness of the sandpaper.

In another study, Nakamura and Takachio (1961) compared the effects of various sanding parameters and made similar observations to previous studies. Coarser sandpaper (*e.g.*, 60 to 80 grit) induces greater grain raising. For the finer sandpaper (*e.g.*, 150 to 240 grit), the grain raising varies significantly with different wood species. In addition, they observed that increased sanding pressure generates greater grain raising.

More recently, Evans (2009) also investigated wood grain raising and arrived at the conclusion that grain raising is greater in low-density wood species than in those with high-density wood. He hypothesized that sanding abrasives tear wood cells along their length, leaving behind strips of loosened cell wall material that tends to lift when exposed to moisture, this being particularly true for low-density wood species. Another conclusion from this work was that fiber sections resulting from the sanding operation swell when wetted, but far less than the swelling due to damage to cell walls. He found that sanding may cause micro-structural damage to the wood surface and induce grain raising, that the degree of grain raising is proportional to grit size, and that grain raising can be reduced by choosing sanding parameters appropriate for each wood species. He also concluded that specimens conditioned under higher moisture conditions tend to yield darker wood hues.

Several patents have been issued in relation to preventing grain raising. One of them describes a process using β-eleostearic acid (Rippey and Dike 1939), while another relies on an aluminum salt (Beane and Safta 1996). These two products tend to decrease the water absorption of the wood fibers. Stains based on milk protein have also been investigated (Burwell 1967).

The objectives of this project are to study the impact of water-based finishes on wood grain raising and more precisely to characterize the grain raising phenomenon by microscopy and profilometry. Another objective is to study the difference in grain raising for solid wood panels and veneers.

MATERIALS AND METHODS

Materials

Yellow birch wood was selected for this research since it is a widely used species for furniture and kitchen cabinets in Canada. Two substrate types were used: sliced veneer and solid sawn wood. Table 1 lists the water-based and solvent-based finishing products used in this study and supplied by CanLak (Canada).

Table 1. Finishing Products Selected for this Study (supplied by CanLak)

Function	**Product number for solvent-based finishes**
Wiping stain*	TEK, RT-41-15, whisky colour
Sealer (nitro-vinyl)	447-181
Catalyzed lacquer	493-135 Syl-Guard
Catalyst	448-024
Function	**Product number for Water-based finishes**
Wiping stain*	TEE, RT-41-16, whisky colour
Acrylic sealer	Aquasyl 185-100
Cross-linked acrylic lacquer	164-035

* Stains pigment volume concentrations were adjusted to obtain the same stain opacity.

Specimen Preparation

The specimens were first conditioned to constant mass at 20 °C and 50% relative humidity (RH) for an equilibrium moisture content (EMC) of 8%. Solid wood was purchased in the wood market and was kiln dry. Sliced wood also was bought in the market, glued with a PVA (type 3) on a HDF substrate, and then conditioned. Visual inspection confirmed that specimens were free of microcracks resulting from drying.

Following preliminary sanding in a wide-belt sander (P100-P120-P150 grit), the veneer specimens were sanded to P180 grit with a Sioux band orbital sander rotating at 12,000 rotations per minute (rpm) with an orbit of 3/32". The aluminum oxide SiaDrive 1949 sand paper was provided by Sia Abrasifs JJS. The lumber panels were sanded to P150 grit with the orbital sander. This selection of grit for both materials (solid wood and sliced veneer) was made to reflect industrial practices.

The wiping stains were sprayed onto the substrates. After one minute, they were wiped with a cloth. The sealers and lacquers were applied with a Falconi reciprocator by the finishing product supplier. One coat of sealer was applied for the solvent-based system, as opposed to two for the water-based system as prescribed by the coating manufacturer. Samples were also prepared with the stains only in order to study the impact of their solvent (water or organic) on the roughness.

Specimen Analysis and Characterization

Overall surface appearance

Specimen surfaces (stained-only specimens) were imaged by optical microscopy in dark-field illumination mode. The microscope used was a Zeiss Axio Imager Z1 model.

The effect of the water-based stain on surface roughness was measured with an Altisurf 520 profilometer from Altimet. This is a non-contact profilometer using confocal chromatic aberration sensors. 3D surface profiles were measured on one specimen in every set of 10. 2D line profiles were measured on all samples but will not be reported here as the trends were similar to the 3D measurements. The measured area was 20 mm x 20 mm with a step size of 5 µm/point. Roughness parameters defined in ISO Standard 25178 (Table 2) were calculated from the height distributions on sub-areas 5 mm x 5 mm in size and averaged. The profiles were corrected for slope and shape (large-scale waving) by fitting a 2nd order polynomial before the roughness parameters were calculated. See ISO 25178 for parameters calculation details.

Table 2. Surface roughness parameters described in ISO Standard 25178

Parameter	Description
Sq	Quadratic average roughness (standard deviation of height distribution)
Sp	Maximum peak height
Sv	Maximum trough depth
Ssk	Skewness of height distribution
Sku	Kurtosis of height distribution
Sdr	Developed Interfacial area ratio

The Developed Interfacial Area Ratio, Sdr, is less well known than other parameters. It is defined as the percentage of surface area contributed by the roughness of the wood as compared to a perfectly flat surface the same size of the measured area. This is a useful parameter to differentiate wood surfaces that have similar roughness amplitude but have different sharpness of their peak to trough transitions. Figure 1 illustrates the schematic conditions of two surfaces with near-identical average roughness, one of them showing double the developed interfacial area ratio of the other due to sharper transitions across peaks and troughs.

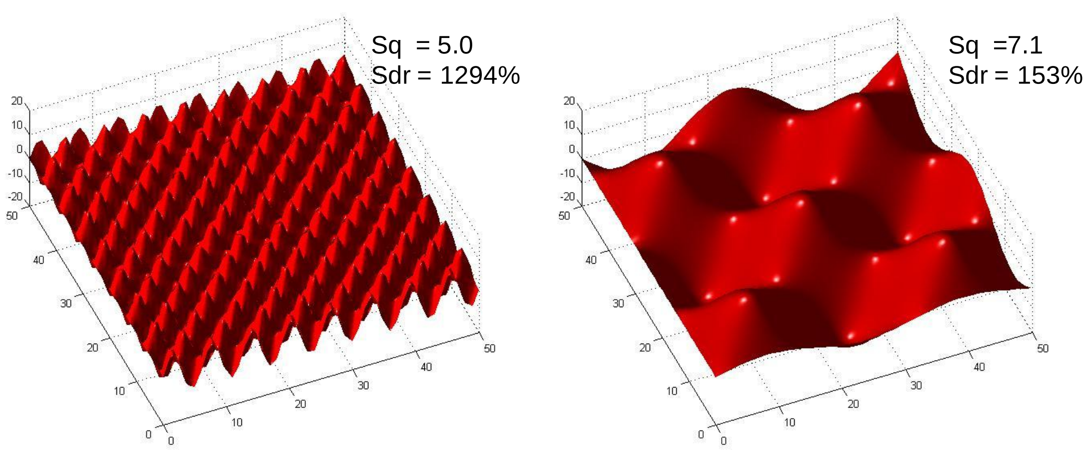


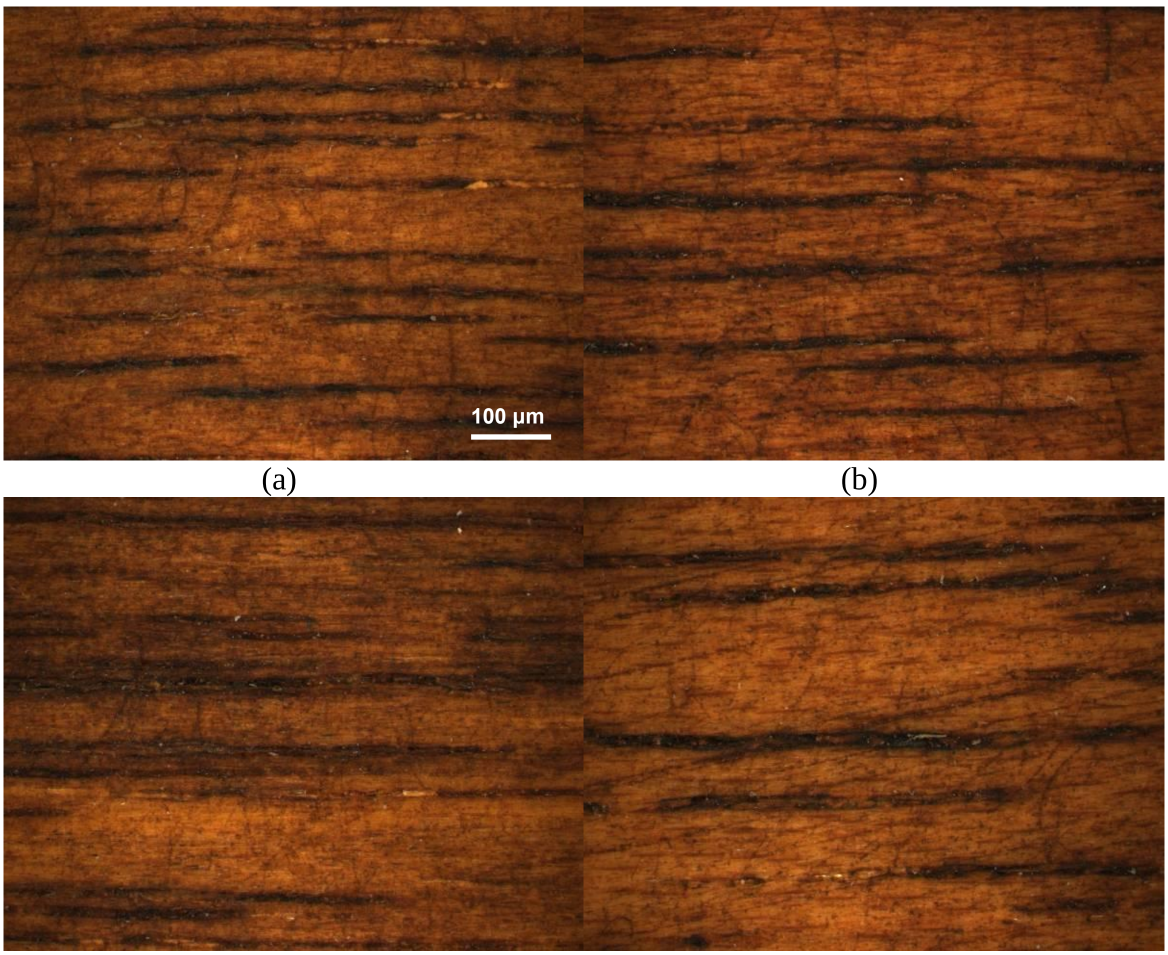
Fig. 1. Comparison of roughness parameters for two hypothetical surfaces

Wood surface morphology was assessed by scanning electron microscopy (SEM). Samples were metalized with a thin gold layer (10-15 nm). Images were recorded at 30 kV. SEM observations were performed on a JEOL 6360.

RESULTS AND DISCUSSION

General Appearance of Stained Surfaces

The appearance of stained-only specimens is shown in Fig. 2. The solid birch specimens treated with water-based and solvent-based stains are shown in Fig. 2a and 2b, respectively, while Figs. 2c and 2d display the veneer specimens treated with water-based and solvent-based stains, respectively. At first sight, few differences could be observed across the different specimens. Stain hues were similar, and greater pigment concentrations were noticeable in vessel sections. All surfaces also displayed arc-shaped marks due to orbital sanding.



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

Fig. 2. Images of stained surfaces (a) lumber with a water-based stain; (b) lumber with a solvent-based stain; (c) veneer with a water-based stain; (d) veneer with a water-based stain

Higher magnification revealed more significant differences between samples prepared with water-based and solvent-based stains (Fig. 3). In fact, it is possible to see that wood samples sanded and coated with water-based stains show less contrast between the vessels and the remaining part of the wood. For the wood samples sanded and coated with solvent-based stains, pigments or dyes seem to go predominantly in the vessels, leading to a better contrast. The unstained veneer panel shown in Fig. 4 clearly highlights the longitudinal parenchyma, and these were also quite visible on both veneer and solid wood specimens treated with a solvent-based stain. On the other hand, it is essentially impossible to observe such parenchyma on specimens treated with a water-based stain, which suggests that the application of a water-based stain hides some details at the wood surface. This also means that reduced grain definition is not exclusively due to sealers and lacquers, but also to the stain, whose pigments may be distributed differently within and over the fibers. The stain also affects the specimen surface topography, which influences the way light is reflected.

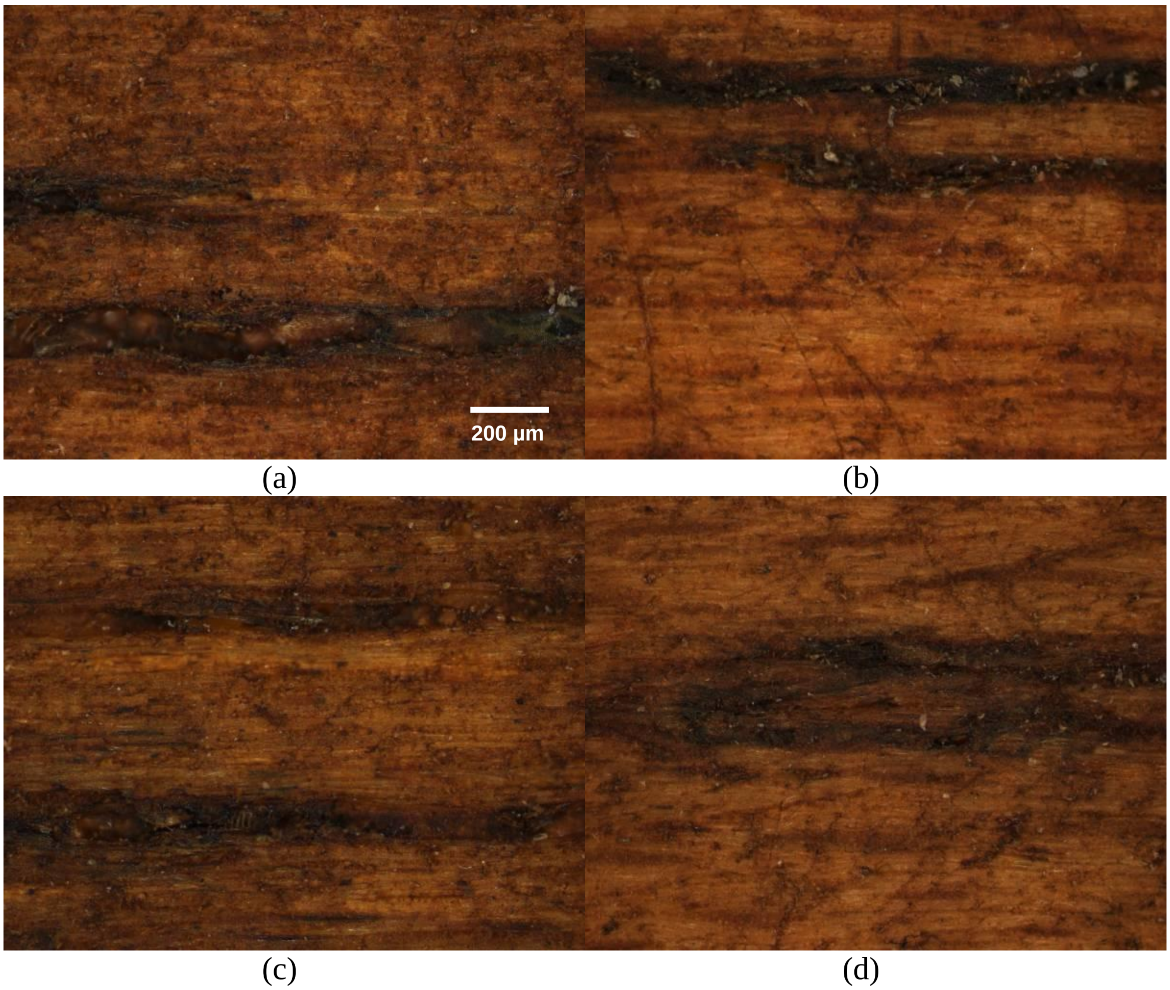


Fig. 3. Images of stained surfaces (a) lumber with a water-based stain; (b) lumber with a solvent-based stain; (c) veneer with a water-based stain; (d) veneer with a water-based stain

The surfaces of specimens treated with a water-based stain also appeared more mottled than those treated with a solvent-based stain, but this may be due to differences between the inorganic pigments and organic dyes that may be used in the manufacture of wood stains. Inorganic pigments are usually dispersed in the solvent, rather than dissolved. As for organic dyes, they are soluble in the solvent, and, once applied to the wood surface, they may re-dissolve when sealers are applied. The selection of inorganic pigments or organic dyes in the preparation of a stain therefore leads to different light reflection patterns. The stains used in our study were formulated with different components, which could explain the appearance variations observed. This remains conjecture, as the study did not investigate differences between pigments and dyes.

Furthermore, water-containing finishes are generally more pleasant to work with, as a painter, and they appear to cause less environmental harm. But the interaction of the water with the wood can cause roughening. Sometimes there is also adhesion problems associated with water-based finishes. Profilometry makes it possible to quantify roughening and evaluate its dependencies.

Fig. 4. Surface of a peeled veneer without finishing products and its longitudinal parenchyma

Effect of Water-based Finishing System on Surface Roughness

Scanning electron microscope

As a first step, SEM images were obtained to compare the effects of water-based and solvent-based treatments on the wood surface in both veneer and lumber specimens.

Figure 5 shows solid wood surfaces. The top two images show surfaces treated with a water-based wiping stain, while a solvent-based stain was applied to the bottom two samples. Images on the left were taken at 75X magnification, and those on the right at 300X.

These images provide a variety of information. One observation was that water-based treatments induced greater surface roughness. According to the prior art, grain raising, which increases surface roughness, may be due to a number of sources, *e.g.*, fiber fragments, individual fibers, bundles of fibers, or even sections, resulted from the sanding operation (Koehler 1932; Marra 1943; Nakamura 1961). According to these studies, raising of sanding sections is far less significant than raising of fiber fragments, fiber bundles, and individual fibers. The results of the present study agree with these previous findings. Sanding sections appeared to contribute very little to increased roughness in water-based treated surfaces. As a matter of fact, sanding sections could be observed in both water-based and solvent-based treated specimens. Orbital sanding patterns were clearly visible with both stain types; they appeared to be more prominent with the water-based stain but seemed to remain a negligible factor. Some fiber fragments were observed to have lifted up in specimens treated with a water-based stain.

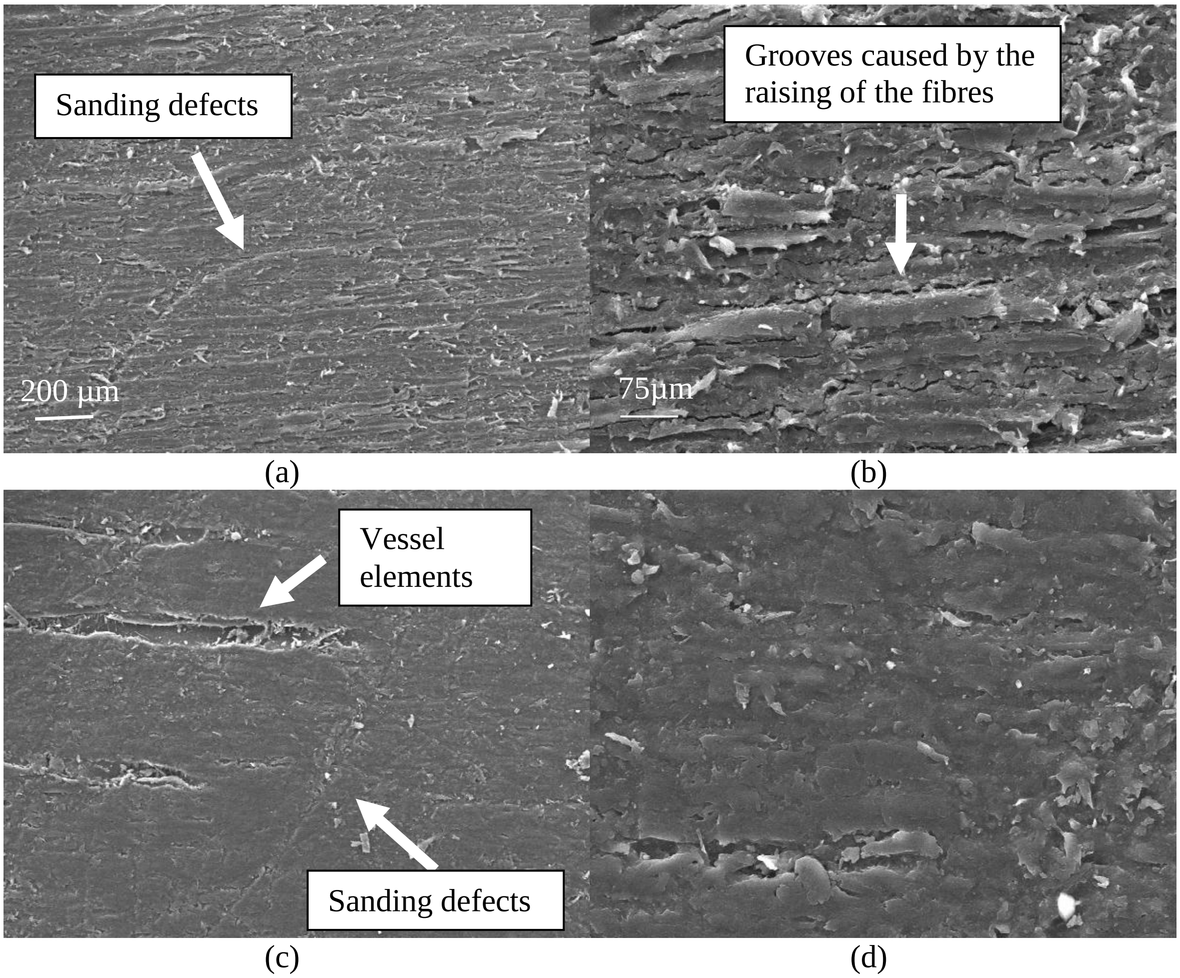


Fig. 5. Lumber samples stained with a water-based stain (a, b) *vs*. a solvent-based stain (c, d)

In surfaces treated with solvent-based stain, fiber fragments were also present, but they appeared to lay flat on the surface rather than stand on end. According to Evans (2009), fiber fragments anchored at just one end naturally tend to twist and rise when exposed to surface water, thus increasing roughness. This would explain why the fiber fragments observed on surfaces treated with a water-based stain were more abundant, and more likely to be standing on end than those found with a solvent-based stain, which seemed to hide them better. Individual fibers and bundles were also observed to rise and separate from neighboring fibers, particularly in lumber. Individual fibers and bundles were also seen to rise and separate from the surface, creating furrows. Most such furrows were parallel to the grain. Irregular edges also confirmed that they were not due to the sanding sections created by wide-belt sanding.

The images obtained from sanded veneer specimens turned out to be similar, as shown in Fig. 6. As with the solid-lumber specimens, surface roughness was greater in the specimens treated with a water-based stain (6a and 6b) than in those treated with a solvent-based stain (6c and 6d). Once again, sanding sections were clearly visible in specimens treated with a water-based stain (Fig. 6 b), as they were on surfaces treated with a solvent-based stain (Fig. 6 d).

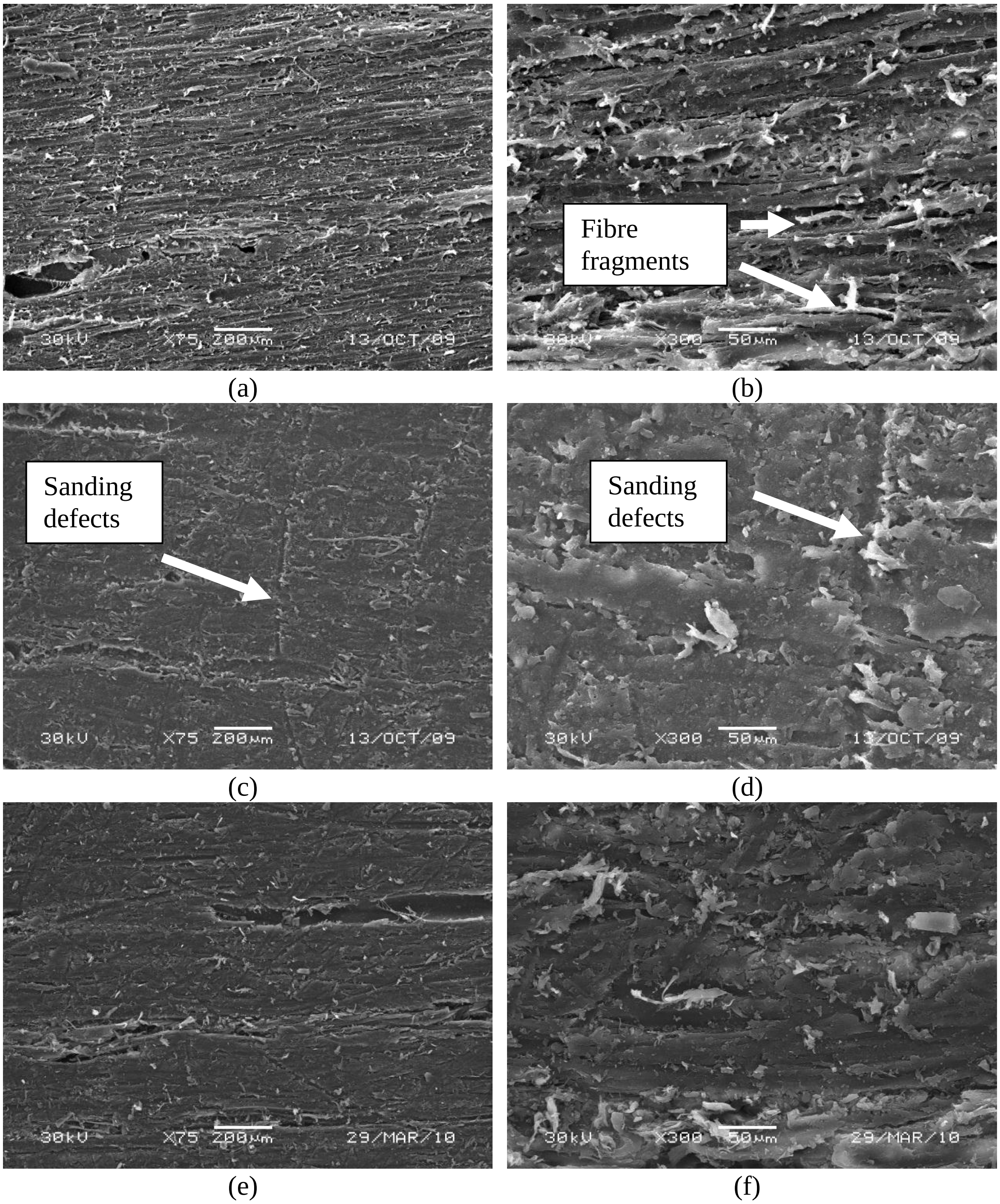


Fig. 6. Veneer samples stained with a water-based stain (a, b); solvent-based stain (c, d) and untreated samples (e, f)

These observations support our conclusion that grain raising occurs mostly by the lifting of fibers, either individually or in bundles. With veneer specimens, sanding generated more fiber fragments that contributed significantly to increased surface roughness. Profilometric measurements aimed at quantifying these results.

Profilometry measurements

Figures 7 and 8 illustrate the 3D topographical data obtained from stained-only specimens. Heights are defined in relation to the mean height of each specimen. Positive values correspond to peaks, while negative values denote troughs. Colors indicate heights, and all surfaces are shown on the same color scale. The roughness parameters calculated from the 3D data (stained-only specimens) are summarized in Table 3. Height histograms for the veneer and solid wood specimens are shown in Fig. 9. Each bar indicates the portion of the specimen's surface area that falls within height intervals of 8 µm above and below the mean height of the specimen.

Table 3. Roughness Parameters Extracted from the 3D Surfaces for Stained Samples (10 samples, 5 roughness measurements per sample)

Sample	Stain	Sq µm	Sv µm	Sp µm	Ssk	Sku	Sdr %
Veneer	Control	8.8	-56.3	36.9	-1.74	9.7	40
Veneer	Water	8.2	-50.8	42.7	-0.58	9.3	21
Veneer	Solvent	5.8	-42.2	18.7	-1.77	10.5	12
Solid	Water	7.5	-69.4	22.9	-3.47	23.3	20
Solid	Solvent	5.6	-46.6	21.2	-2.54	15.3	13

Veneer specimens

The 3D images shown in Figs. 7 and 8 yielded the same information as the SEM results. Prior to staining, the sanded veneer specimens exhibited some degree of roughness due to raised fiber fragments and furrows between the fibers. After treatment with the water-based stain, fibers swelled, which amplified localized roughness in a directional manner, creating new furrows as fibers separated from adjacent fibers. The application of the stains is expected to decrease the roughness. For the water-based stain, Sq roughness did not decrease significantly (Table 3), but the developed interfacial area ratio, Sdr, decreased by 50% as some of the fibers were flattened and the troughs were filled. Although there was an overall decrease in roughness with the application of the stains, the water-based stain seemed to make some of the fiber fragments rise even higher over the specimen average than before staining, as the proportion of heights above 16 µm is higher for the stained specimen as compared to the control (Fig. 9).

The solvent-based stain produced a significant decrease in Sq roughness as well as a 70% decrease in Sdr, resulting in a smoother surface than for the water-based stain. Fiber swelling was minimal, and the stain effectively smoothed down fiber fragments left from the sanding operation. Fiber fragments remained visible, but with softened edges. The presence of cracks due to the veneer processing may have contributed to the roughness, but these were not analyzed separately for this study.

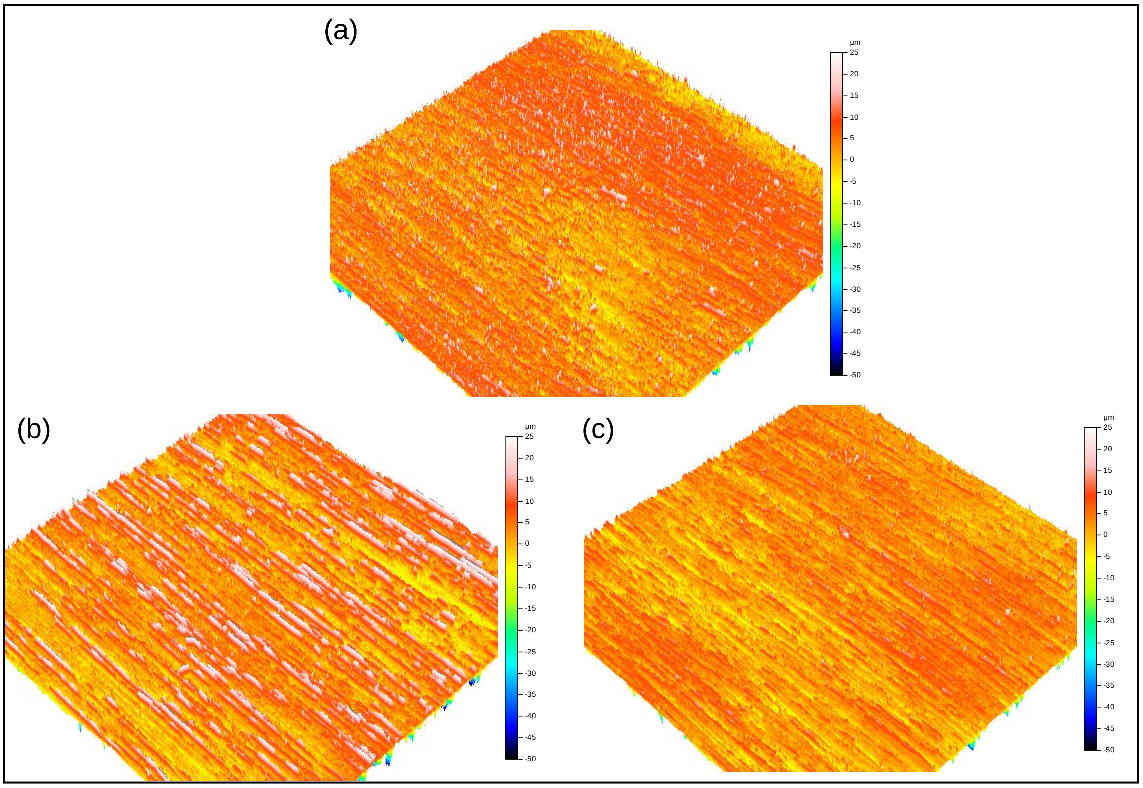


Fig. 7. 3D Renderings of profilometric measurements on sanded veneer without finishing products (a); with a water-based stain (b); with a solvent-based stain (c). Color scale goes from -50 µm to 25 µm Surface dimensions: 20 x 20 mm

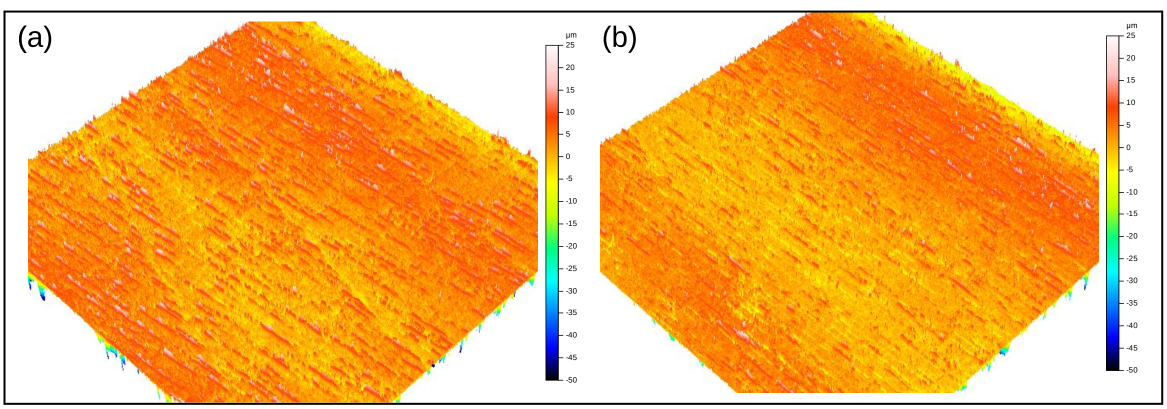


Fig. 8. 3D Renderings of profilometric measurements on edge-glued yellow birch panels (a) with a water-based stain (b) with a solvent-based stain. Color scale goes from -50 µm to 25 µm Surface dimensions: 20 x 20 mm

Lumber specimens

As shown in Figs. 7 and 8, as well as in Table 3, grain raising due to treatment with a water-based stain was less severe with solid-wood than with veneer specimens, and the difference between water-based and solvent-based was consequently reduced.

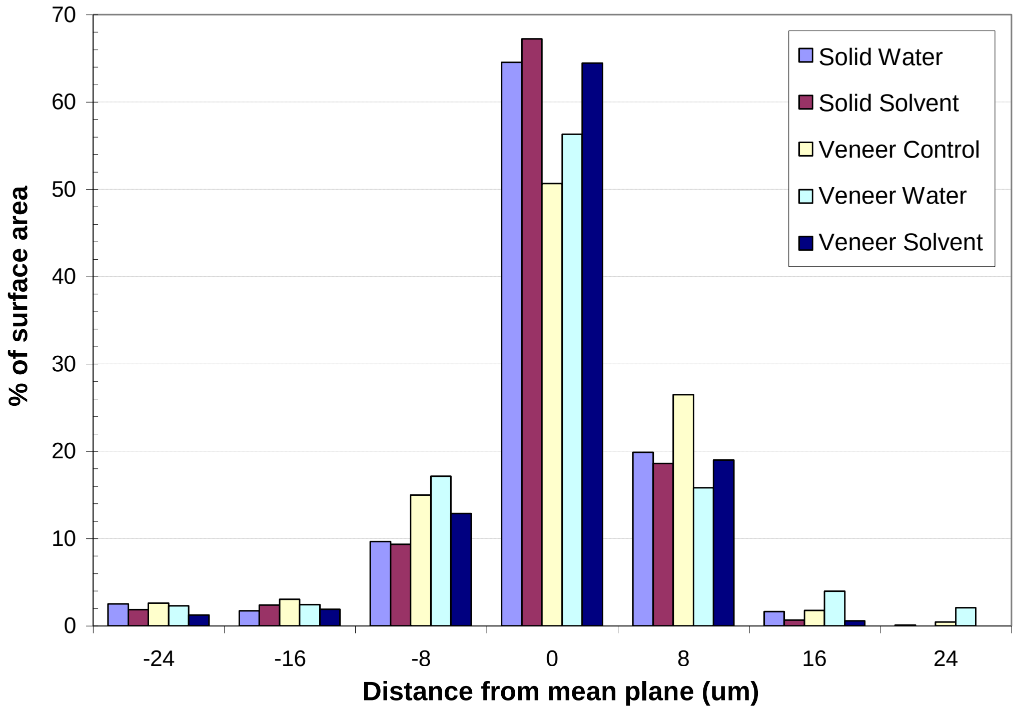


Fig. 9. Histograms of the heights on yellow birch solid and veneer samples

As already stated, the veneer specimens sanded with lab scale equipment and factory sanding of the solid-wood panels yielded superior results. Unfortunately, a control lumber sample without stain was not available for measurement, which could have allowed us to quantify the difference in surface preparation quality. The lower incidence of fiber fragments on the solid-wood surface may explain a reduced level of grain raising. These results demonstrate the need to limit surface debris in the sanding operation, especially when using water-based products as they tend to induce more grain raising.

CONCLUSIONS

1. The first objective of this study was to investigate the factors responsible for the differences observed in the appearance of water-based and organic solvent-based stains in wood products and characterize grain raising due to water-based stains. The study demonstrated that the appearance of wood surfaces treated with water-based and solvent-based stains is affected by a number of factors, including grain raising, surface preparation quality (sanding in this case), and substrate type (veneer or lumber). These results agree with the conclusions of previous studies (Evans 2009; Marra 1943), showing the importance of sanding methods in the generation of grain raising (fiber fragments) and finish quality.
2. The developed interfacial area parameter calculated from profilometric data can provide valuable information, as it captures both grain roughness and small-scale roughness due to raised fiber fragments. Although based on 3D measurements and

relatively sophisticated instrumentation, a similar parameter could be defined using 2D measurements for easier application in industry.

3. Another objective of the study was to investigate the effect of substrate type (veneer or lumber) on the final appearance. Differences between sawn lumber and peeled veneer appeared minor, although the lumber exhibited less significant differences between water-based and solvent-based finishing systems.
4. Grain raising is a critical factor for the appearance of the finished products. Improvements in this regard would reduce the amount of fiber fragments on the wood surface, but they would be difficult to eliminate.

ACKNOWLEDGMENTS

The authors wish to thank Peintures Can-Lak for their support.

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Article submitted: May 30, 2012; Peer review completed: October 8, 2012; Revised version received and accepted: December 21, 2012; Published: February 26, 2013.