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# Interactive effect of surface densification and post-heat-treatment on aspen wood

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ABSTRACT

Surface densification technique can be used to enhance mechanical properties of low-density wood at a relative low temperature such as 145 °C. However, the final dimensions of densified wood products are not stable when exposed to cyclic weathering. Post-high-temperature heat-treatment could assist in solving this problem through the modification of chemical components in wood. This study examined the interactive effect of surface densification and post-heat-treatment on aspen (*Populus tremuloides*). Thickness swelling and other selected properties of heat-treated surface densified aspen were compared to untreated aspen. As expected, the heat-treatment significantly improved the dimensional stability of surface densified aspen and reduced the mechanical properties to some degree. However, the mechanical properties of heat-treated densified specimens were still greater than those unheat-treated undensified ones.

## 1. Introduction

The utilization of low-density woods for flooring is limited due to their lower surface hardness and wearing resistance. To increase the use of low-density woods in flooring applications, surface densification technology has been developed with a minimum loss of wood volume. Onishi et al. (1984) densified the surface of Sitka spruce (*Picea sitchensis*) using polypropylene film through a roller press. The temperatures used were 150 and 200 °C and the compression ratios used were 5 and 10%. They discovered that the hardness, abrasion resistance and modulus of rupture were increased by 30, 600 and 21%, respectively. Inoue et al. (1990) carved 2 mm wide and 5 mm deep grooves on the surface of softwood lumber specimen with an interval of 150 mm across the grain direction, soaked the grooved surface with water, and heated using a microwave. After densification at a surface compression ratio of about 45%, they produced surface densified lumber from sugi (*Cryptomeria japonica*), hinoki (*Chamaecyparis obtuse*) and western hemlock (*Tsuga heterophylla*), and found an increase in hardness and abrasion resistance of 120–150% and 40–50%, respectively. Rautkari et al. (2008) employed the linear vibration friction technique to densify the surface of Norway spruce (*Picea abies*) wood. They first preheated the surface layers of wood specimens to 100 °C, which were fixed on a so-called welding machine. Then, the specimens were shaken at a frequency of 100 Hz, amplitude of 3 mm, and pressure of 2.2 MPa. Finally, a pressure of 0.58 MPa was maintained on the specimens at the end of vibration until the surface temperature cooled to 60 °C. Rautkari et al. (2008) found that the specimens were actual compressed by only 2.7% to their original thickness, however, the surface hardness was increased by 137%. The compression ratio of 2.7% was the overall value across the thickness. The compression ratio in the surface layers could be much larger, which was not reported by Rautkari et al. (2008). With an aim at developing the surface densification technology on a commercial scale, Lamason and Gong (2007) studied the surface densified aspen (*Populus tremuloides*) by optimizing the thermo-mechanical densification parameters. Their results showed that the hardness, modulus of elasticity (MOE), and nail withdrawal resistance of surface densified aspen were increased by 140, 23 and 132%, respectively. The compressed thickness of surface densified wood could be almost recovered to its original value after soaking in boiling water. Although such a severe condition (i.e. soaking in boiling water) does not exist in the actual applications of densified wood, the dimensional stability could cause some problems such as warping and delamination of densified laminated wood products when exposed to moisture in service. These phenomena might be explained in light of the release of internal residual stresses existing in densified wood. Gong et al. (2008) separated the residual stresses in densified balsam fir (*Abies balsamea*) and eastern white pine (*Pinus strobus*) into physical and mechanical components, and developed a mathematical model describing the recovery of mechanical residual stress.

An attempt has been made to fix the compressed deformation of densified wood, which includes physical and chemical treat-

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ments. Inoue et al. (1990) and Kamke (2004) densified wood in a sealant chamber with heat and steam. Their research showed exceptional results in that the compressed deformation could be permanently fixed. However, their trials were limited to the laboratory scale. Such a thermo-mechanical densification process could be quite costly for industrial production. Fukuta et al. (2008) drilled 1.3 mm holes, following two drilling patterns, in boards cut from the heartwood of Japanese cedar (*Cryptomeria japonica*). A water-soluble, low molecular weight phenolic resin was impregnated using platen pressing and vacuum treatments. The specimens were pressed to 50% of their original thickness at room temperature. They discovered that the recovery ratio (recovered thickness/compressed thickness) of the specimens without drilled holes was 80% compared to 30% for those specimens with drilled holes. This recovery ratio had two components, the springback after pressing and swelling after 2 h boiling treatment. A 10% weight gain was observed in those specimens with drilled holes. Additionally, the resin impregnation did reduce the dimensional recovery, however, it could raise a potential environmental issue due to the use of chemicals.

Heat-treatment (or thermal modification) technology has been well developed to improve dimensional stability. This technology heats wood to a temperature close to or above 200 °C for several hours in an atmosphere with low oxygen level, a non-combustible gas such as nitrogen, or oil. The principle of this process is that heat alters the chemical composition of wood resulting in a change in the physical properties of the wood. Tjeerdsma et al. (1998) examined the effect of thermal modification process on the chemical degradation of wood components, and discovered that hemicelluloses were most sensitive to heat, and lignin the least. Syrjänen and Kangas (2000) reported that the thickness swelling and equilibrium moisture content of heat-treated wood was reduced by 80–90% and 40–60%, respectively, compared to untreated wood of the same species. The heat-treatment technology could be commercialized due to its acceptable cost and environment friendly process (Rapp, 2001). Welzbacher et al. (2008) took two steps to treat Norway spruce (*Piece abies*) in the laboratory. They densified specimens at four temperatures in combination with four pressing times, and then treated in an oil heat-treatment process at three temperatures for 2 and 4 h. The compression ratio used varied from about 40 to 50%. They found that the compressed dimension was almost completely fixed for those specimens that were oil-treated at temperatures over 200 °C. Welzbacher et al. (2008) also indicated that a one-step treatment involving mechanical densification plus thermal modification was not recommended since it could not achieve a suitable dimensional stabilization for practical application.

The interactive effect of surface densification and post-heat-treatment on surface densified aspen was investigated in this study. The thickness swelling and other selected properties of post-heat-treated surface densified wood were analyzed and compared to those surface densified wood without heat-treatment. These properties included density, hardness, MOE, nail withdrawal resistance, and wearing resistance.

## 2. Materials and methods

Aspen (*Populus tremuloides*) having an oven-dried density between 0.37 and 0.45 g/cm$^3$ were selected for this study. Plain sawn clear wood stick specimens were prepared with dimensions of 25 mm (1 in.) thick (radial direction) by 38 mm (1.5 in.) wide (tangential direction) by 280 mm (11 in.) long (grain direction). Specimens were air-dried and conditioned to 12% moisture content at 20 °C and 65% relative humidity for at least 4 weeks prior to treatments. Eight groups of specimens (four for surface densification and four for controls) were prepared based on the density distribution. All specimens with density outside the range [mean ± 1.96 × standard deviation] were rejected. Each group had three specimens, for a total of 24 specimens. The optimized surface densification parameters used in this study were previously decided by Lamason and Gong (2007). The parameters used were as follows, an overall compression ratio of 24% (that was defined as the ratio of diminished thickness to the initial thickness in radial direction), press temperature of 145 °C and press closing time of 7 min. The specimens were then kept under pressure for 5 min. Prior to removal of pressure, the platens were cooled to room temperature. The press opening time was about 1 min. The final thickness of surface densified wood was about 19 mm.

Post-heat-treatment process on specimens was performed in a 1 m$^3$ chamber equipped with steam ejection in a mill in Quebec, Canada. Both surface densified and undensified specimens were treated at three temperatures, HT1 (190 °C), HT2 (200 °C) and HT3 (210 °C). As comparison property indexes, density, thickness swelling, surface hardness, MOE, nail withdrawal resistance and surface wearing resistance were measured with reference to ASTM Standard D143-94 (ASTM, 2004). The MOE, nail withdrawal resistance and surface hardness tests were carried out on an Instron testing machine. The testing procedures and set-up were also referenced to ASTM Standard D143-94. The span-to-depth ratio used in bending tests was 14.

The thickness swelling test was conducted as follows, specimens were vacuum-pressure impregnated by water for 1 h, placed in boiling water for 2 h and then dried in an oven at 103 ± 2 °C until no change in weight was observed. The thickness swelling was calculated by

$$\text{Thickness swelling}(\%) = \frac{T_R - T_1}{T_0 - T_1} \times 100 \tag{1}$$

where $T_R$ is the thickness after the recovery test, $T_1$ is the thickness after densification, and $T_0$ is the thickness before densification.

A commercial Taber 5130 Abraser was used to evaluate the wearing resistance. An abrasive wheel was mounted on a test specimen and rotated for 500 cycles. The wheel (# H-22) was weighed with a 1 kg load. The specimen was made by bonding side-by-side three 35 mm wide sticks. The overall specimen dimension was 102 mm in width, 102 mm in length and 19 mm in thickness. Wearing resistance was determined based on the loss of percentage weight before and after abrasion, which was calculated by

$$\text{Wearing resistance}(\%) = \frac{\begin{array}{c}\text{Weight of specimen before abrasion}\\ -\text{ weight of specimen after abrasion}\end{array}}{\text{Weight of specimen before abrasion}} \times 100 \tag{2}$$

In addition, the density profile of each specimen was scanned across the radial (thickness) direction using a commercial X-ray scanner (Model QTRS-01X, Quintek Measurement Systems, Tennessee, USA).

## 3. Results and discussion

### 3.1. Density

Table 1 shows that the effect of heat-treatment on density differed between undensified and densified specimens. Overall, the effect of heat-treatment on undensified aspen was very slight, causing a loss of density of 2%. However, such a treatment had a stronger influence on densified aspen, resulting in a loss of density of 11%. Heat transfers much faster in the higher density materials than lower ones. At the same treating condition, the densified specimens might experience a longer time at the target high temperature